PRESSURE INJURY RISK AMONG CRITICAL-CARE PATIENTS

by

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ABSTRACT

Hospital-acquired pressure injuries (PI) are localized areas of damage to the skin, underlying tissue, or both, as a result of pressure. Critical-care patients represent a highly specialized patient population, and currently available risk-assessment scales, such as the Braden scale, tend to identify most critical-care patients as being "at risk" for pressure injuries, and therefore are of limited clinical utility. The purpose of this dissertation was to (a) conduct a systematic review of the literature to identify independent risk factors for pressure injuries, (b) use longitudinal analysis to identify the hazards of developing a pressure injury based on changing Braden Scale total and subscale scores, and (c) develop a PI prediction model. We conducted our systematic review based on standardized criteria and developed a tool for quality assessment based on a literature search and input from experts. Mobility/activity, age, and vasopressor infusion emerged as important risk factors, whereas results from other risk categories were mixed. For the Braden scale analysis and the predictive model we used electronic health record cases (*N*=6,376). We employed time-dependent Cox regression to determine the hazards of developing a pressure injuries based on the Braden scale subscale scores. With the exception of the friction and shear subscales, patients of all ages with midrange Braden scale scores were more likely to develop pressure injuries than their counterparts with higher risk scores. We developed a predictive model using random forest analysis. The model, an ensemble classifier, was composed of 500 decision trees, each using a random

subset of 4 of 20 clinical features. The area under the receiver operating characteristic curve was 0.9 for the outcome ≥category 1 pressure injuries and 0.87 for the outcome ≥category 2 pressure injuries. The most important variables in our model in descending order based on the mean decrease in accuracy were longer surgical duration, lower hemoglobin, higher creatinine, older age, higher glucose, lower body mass index, lower albumin, and higher lactate. Due to our model's relatively strong performance, it may be useful for directing preventive interventions that are not feasible for every patient due to cost.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHRQ	Agency for Healthcare and Research Quality
APACHE	acute physiology and chronic health evaluation
ASA	American Society of Anesthesiologists
CAM	confusion assessment method
CI	confidence interval
CURS	Corneil ulcer risk score
DTI	deep tissue injury
EDW	University of Utah Enterprise Data Warehouse
EHR	electronic health record
EPUAP	European Pressure Ulcer Advisory Panel
GCS	Glaslow Coma Scale
HAPI	hospital-acquired pressure injury
HQS	high-quality study
HRR	hazard rate ratio
ICU	intensive care unit
ID	identification
JA	Jenny Alderden
JR	June Rondinelli
JRB	Jessica Richards Bergtonelli
LB	Lacey Bunker

LOS	length of stay
LQS	low-quality study
MAP	mean arterial pressure
MDA	mean decrease in accuracy
MODS	multiple organ dysfunction syndrome
MQS	moderate-quality study
NAS	nursing activities score
NPUAP	National Pressure Ulcer Advisory Panel
NPV	negative predictive value
NR	not reported
OOB	out of bag
PI	pressure injury
PPPIA	Pan Pacific Pressure Injury Alliance
PPV	positive predictive value
RDS	Research Data Service
Ref	reference
RF	random forest
Riker	Riker sedation and agitation scale
ROC	receiver operating characteristics
SAPSI	Simplified Acute Physiology Score
SCI	spinal cord injury
SOFA	sequential organ failure assessment
TISS	trauma injury severity score
VLQS	very-low-quality study

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CHAPTER 1

INTRODUCTION

Hospital-acquired pressure injuries (HAPIs) occur among 3%–24% of patients in the United States and result in longer hospitalization, increased morbidity, and human suffering (Frankel, Sperry, & Kaplan, 2007; Graves, Birrell, & Whitby, 2005; Slowikowski & Funk, 2010). Despite increased attention, the problem of pressure injuries during hospitalization is growing. The 2006 Healthcare Cost and Utilization Project determined that pressure injury incidence increased 63% from 1993 to 2003. By 2006, the same project documented an 80% increase in pressure injuries (Russo, 2008). Among hospitalized older adults, pressure injuries are twice as common among individuals who are admitted to the intensive care unit (ICU), which is particularly concerning because older age is a risk factor for slower pressure injury healing (Alderden, Whitney, Taylor, & Zaratkiewicz, 2011; Baumgarten et al., 2008).

Although HAPIs are common, some pressure injuries can be prevented using measures that are not feasible for every patient because of cost (Jackson et al., 2011). In addition, accurate risk assessment will enable prompt recognition and treatment of pressure injuries that occur among high-risk patients, which is important because early stage pressure injuries are highly treatable (Halfens, Bours, & Van Ast, 2001). Therefore, recommended standards of practice include conducting structured pressure injury risk

assessments (National Pressure Ulcer Advisory Panel, European Pressure Ulcer Advisory Panel, & Pan Pacific Pressure Injury Alliance, 2014); however, discernment of high-risk individuals in the ICU is problematic because the risk-assessment scales currently used among ICU patients tend to identify almost all patients as being at high risk (Keller, Wille, van Ramshorst, & van der Werken, 2002). For example, the Braden Scale is the most commonly used scale among ICU patients in the United States, despite low specificity (7% specificity at 100% sensitivity) in that population (Cox, 2011).

The Braden Scale is the sum of six items that the authors of the scale refer to as subscale scores; it was developed to be used for planning effective pressure injury prevention interventions. However, the use of summative scores to ascertain pressure injury risk is controversial; some authors propose that Braden Scale subscale scores, rather than the cumulative score, should be the focus of pressure injury prevention efforts (Gadd, 2014). Studies detailing pressure injury risk associated with Braden Scale subscale scores among critical-care patients are limited (Cox, 2012).

A pressure injury risk-assessment tool with acceptable specificity among ICU patients is needed; however, before such a tool can be developed, information about which factors best predict pressure injury development is necessary. Although some recent studies have examined pressure injury risk among ICU patients, there is little consensus about which factors predict risk because existing studies are highly variable in terms of risk factors examined, study population, and pressure injury measurement methodology. In addition, information about the relationship between Braden subscale scores and pressure injury development is needed.

Problem Statement

The purpose of this dissertation is to evaluate the risk for pressure injuries among critical-care patients. The specific aims are (a) to conduct a systematic review of the literature to identify factors that are independently associated with increased risk for pressure injuries among critical-care patients; (b) to identify pressure injury risk associated with the Braden Scale total score and various subscale scores among critical-care patients, and to ascertain whether the risk represented by subscale scores is different between older and younger patients; and (c) to develop a model to predict pressure injury risk among critical-care patients.

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CHAPTER 2

REVIEW OF THE LITERATURE

Pressure Injury Categories

Pressure injuries (PIs), formerly called pressure ulcers, are localized areas of injury to skin and/or underlying tissue that occurs as a result of pressure or pressure in combination with shear (National Pressure Ulcer Advisory Panel [NPUAP], 2016). There are six categories of pressure injuries defined by NPUAP. Category 1 PIs are areas of nonblanching redness or discoloration in intact skin. Category 2 PIs represent partial-thickness tissue loss with exposed, viable dermis. Category 3 PIs are full-thickness wounds that do not extend into muscle, bone, or tendon. Category 4 PIs are full-thickness wounds that extend down to muscle, tendon, or bone. Deep-tissue injuries are areas of intact or nonintact skin with a localized area of persistent, nonbleachable, deep red, maroon, or purple discoloration revealing a dark wound bed or blood-filled blister. Finally, unstageable pressure injuries are areas of full-thickness tissue loss that cannot be evaluated because the area is obscured by eschar or slough.

Scope of the Problem

Pressure injuries are one of the oldest documented medical problems. In the 19th century, Jean-Martin Charcot, a prominent French physician, described PIs and referred to them as “decubitus ominosus”—recognizing that the presence of a PI was an ominous

finding (Levine, 2005). Despite major advancements in our understanding of the etiology and treatment of PIs, they remain a serious medical problem today.

PIs affect 2.5 million patients in the United States every year, with resulting medical costs ranging from $9.1 to $11.6 billion per year (Agency for Healthcare and Research Quality [AHRQ], 2016). AHRQ (2016) estimates that development of a PI adds between $20,900 and $151,700 to each hospital stay. Among hospitalized older adults, PIs are twice as common among individuals who are admitted to the intensive care unit, which is particularly concerning because older age is a risk factor for slower PI healing (Alderden, Whitney, Taylor, & Zaratkiewicz, 2011; Baumgarten et al., 2008).

In addition to financial cost, PIs impose significant human suffering. They are an inherently painful condition; multidisciplinary pain-management techniques, including medication administration, are advised for managing PI pain (Pieper, Langemo, & Cuddigan, 2009). In addition to causing physical pain, PIs may inhibit mobility because it is necessary for the person with the PI to avoid body positions that exert any pressure on the existing wound (Gorecki, Nixon, Madill, Firth, & Brown, 2012). Unsurprisingly, people with PIs report lower health-related quality of life than their counterparts without PIs, and are more likely to suffer from depression compared to people with similar health profiles who do not have a PI (Galhardo, Garroni Magalhaes, Blanes, Juliano, & Masako Ferreira, 2010).

Risk Factors for Pressure Injuries

Studies detailing risk factors for PIs among critical-care patients are highly variable in terms of study quality, risk factors evaluated, and even PI definition (category 1 and greater vs. category 2 and greater). Chapter 4 is a systematic review aimed at

identifying independent risk factors for PI development. Results from the systematic review underscore the importance of avoiding overinterpretation of a single study, and the importance of taking study quality into consideration when reviewing risk factors. Mobility/activity, age, and vasopressor infusion emerged as important risk factors for PI development, whereas results for risk categories that are theoretically important, including perfusion (apart from vasopressor infusion), nutrition, and general health status, were mixed. Methodological limitations across studies limit generalizability of results, and future research is needed, particularly to elucidate risk conferred by altered perfusion, vasopressor infusion, malnutrition, and severe illness.

The Braden Scale

The purpose of the Braden Scale (Bergstrom, Braden, Laguzza, & Holman, 1987) is to help clinicians plan effective PI prevention interventions. The scale is comprised of six items, which the authors refer to as subscales: sensory perception, moisture, activity, mobility, nutrition, and friction/shear. Total scores range from 6 (highest risk) to 23 (lowest risk).

Prior studies examined the predictive value of the Braden Scale total score among critical-care patients, with mixed results. In general, the Braden Scale total score identifies most critical-care patients who go on to develop a PI (high sensitivity), but classifies most critical-care patients as being "at risk" for PIs. Low specificity is problematic in other populations, as well: The authors of a 2016 meta-analysis concluded that the total Braden score presents low predictive specificity for PIs in long-term-care residents (Chen, Shen, & Liu, 2016). In an effort to address the Braden total score's low specificity, some authors have proposed that Braden Scale subscales should be the focus

of prevention efforts because the subscale scores provide information specific to the individual patient (Tescher, Branda, Byrne, & Naessens, 2012).

Although some hospital systems in the United States have already transitioned to a subscale-based approach for PI risk assessment, few studies have examined Braden Scale subscale scores among critical-care patients. Cox (2012) conducted a systematic review of the literature and concluded that more information was needed. Among studies that examined Braden subscale scores, four subscales (friction and shear, moisture, mobility, and sensory perception) demonstrated some predictive value on multivariate analysis, whereas two (nutrition and activity) did not (Bours, De Laat, Halfens, & Lubbers, 2001; Carlson, Kemp, & Shott, 1999; Cox, 2011, 2012; Jiricka, Ryan, Carvalho, & Bukvich, 1995). A major methodological limitation noted by Cox (2011) was the lack of a repeated-measures approach; however, the subscale scores were taken from a single point in time (e.g., admission) or were averaged in some way, which failed to capture the dynamic nature of critical-care patients' physiologic status.

In an effort to analyze the risk represented by the various Braden subscales, Gadd (2014) conducted a case study that included chart reviews of 20 patients with hospital-acquired PIs, and concluded that some injuries might have been avoided if preventive interventions based on Braden Scale subscale scores were implemented. Information is still needed pertaining to the risk represented by the various subscale scores, however.

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CHAPTER 3

METHODS

Design

We conducted a systematic review to identify risk factors that were independently predictive of pressure injury (PI) development among critical-care patients. Next, we used a descriptive, longitudinal, correlational, retrospective design to investigate the relationships between Braden Scale and subscale scores with PI development among critical-care patients, and to develop a model to predict PI risk among critical-care patients.

Systematic Review

The purpose of our systematic review was to identify independent risk factors for PI development among critical-care patients. We undertook a systematic review of primary research based on standardized criteria set forth by the Institute of Medicine (Eden, Levit, Berg, & Morton, 2011). A research librarian coordinated the search strategy and checked the completed search to ensure that it was reproducible.

We adapted inclusion criteria based on the method employed by Coleman and colleagues (2013), to include (a) primary research; (b) English language; (c) adult sample; (d) intensive care unit (ICU) setting; (e) prospective cohort, retrospective record review, or controlled trial; and (f) identification of independent risk factors for PI

(multivariate analysis). Exclusion criteria included the following: (a) limited to a pediatric patient population (age <18 years), (b) >25% of the study population being excluded from analysis because of loss to follow up or missing records, (c) a cross-sectional study, (d) limited to evaluation of a PI risk-assessment scale, and (e) limited to spinal cord injury (SCI) patients (due to the specialized physiology involved in SCIs and the associated risk for PI among individuals with SCI (Rappl, 2008).

We searched the medical subject headings *pressure injury* and *intensive care units* in addition to field-restricted keywords in the following databases: CINAHL (EBSCOhost), the Cochrane Library (Wilson), Dissertations & Theses Global (ProQuest), PubMed (National Library of Medicine), and Scopus. We downloaded our final results on December 17, 2016.

Two researchers (JA and LB)[1] screened abstracts for relevance. Abstracts assessed as potentially relevant were checked by a third reviewer (JR). A single reviewer (JA) extracted data related to study characteristics, and a second reviewer (JR or JRB) checked the extracted data. Based on a literature search, we developed a tool for assessing study quality using a combination of currently available tools and expert input. Studies were classified as being of high, moderate, low, or very low quality. We used the method developed by Coleman and colleagues (2013) to generate evidence tables and a summary narrative synthesis by domain and subdomain.

Study Setting

University Hospital in Salt Lake City, Utah, is a 485-bed, level-1 trauma and teaching hospital. The surgical ICU was a 12-bed unit serving a diverse group of surgical

[1] JA = Jenny Alderden; LB = Lacey Bunker; JR = June Rondinelli; JRB = Jessica Richards Bergtonelli.

patients, including transplant patients. The cardiovascular ICU was a 12-bed unit for individuals who underwent cardiothoracic surgery. Nurses in the surgical and cardiovascular ICUs cared for patients using a 1 nurse:1 patient or a 1 nurse:2 patient ratio, depending on patient acuity.

Sample

The final sample consisted of 6,377 patients admitted to the surgical and cardiovascular critical-care units at University Hospital between January 1, 2008 and May 1, 2013 who met inclusion criteria, which were admission to the adult surgical ICU or cardiovascular ICU, either directly or following an acute-care stay. We included individuals younger than 18 years who were admitted to the adult ICU in an effort to study the Braden Scale as it was actually used among all patients in the adult surgical ICUs; however, we excluded patients with PIs present on admission to the ICU due to concern about misattribution of community-acquired PIs as hospital-acquired PIs.

Measures

During the time period encompassed by the study, all charting was recorded in the electronic medical record system PowerChart® (2016). It was standard practice for nurses in the ICU to record vital signs at least hourly, and to conduct a head-to-toe assessment, including a skin assessment, every 4 hr. Nurses recorded the Glaslow Coma Scale, Richmond Sedation and Agitation Scale, Confusion Assessment Method Intensive Care Unit, and Braden Scale (Braden & Bergstrom, 1987) scores at least once during each 12-hr shift (twice per day). The nurses received annual training on the Braden Scale and also on PI identification.

Outcome Variable

The primary outcome variable was a hospital-acquired pressure injury: category 2–4, deep tissue injury (DTI), or unstageable injury. The secondary outcome variable defined in the analysis for Aim 1 (Braden Scale) was a HAPI of any category (1–4, DTI, or unstageable). We did not include category 1 pressure injures in the primary analysis due to concern about the difficulty of differentiating between transient redness caused by friction or dermatitis versus true tissue injury (Bruce, Shever, Tschannen, & Gombert, 2012); however, we did include category 1 injuries in a separate, secondary analysis in an effort to capture the full spectrum of tissue injury.

Predictor Variables

We selected predictor variables based on two factors. First, our systematic review of the literature enabled us to select potential risk factors that were identified in other studies. Second, we met with clinicians at the study site to obtain their hypothesis about potential predictor variables. The latter mechanism was particularly important in our variable selection process because current studies show that the available risk-assessment tools are no better at predicting PI development than the gestalt judgments of clinicians themselves (Webster et al., 2011). Therefore, we wanted to know which factors clinicians were assessing in their clinical decision-making process. The final variable list reflects input from the following clinician groups: anesthesia; intraoperative nursing; wound, ostomy, and continence nursing; intensivist physician; and critical-care nursing (medical and surgical).

Braden and Bergstom's (1987) conceptual schema for studying the etiology of pressure sores served as the conceptual model for variable selection (see Figure 3.1). The

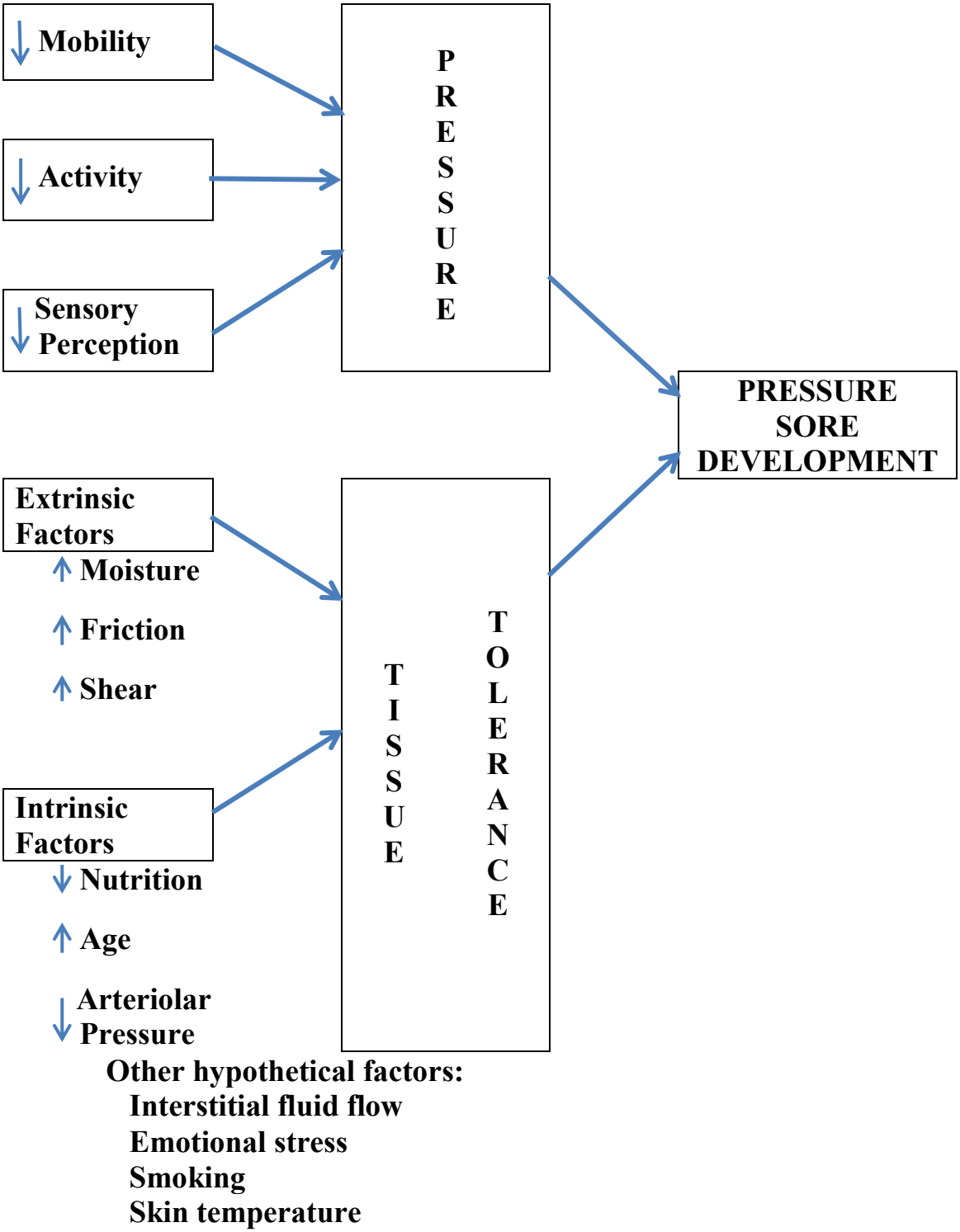

Figure 3.1 Braden and Bergstrom's 1987 conceptual schema (Bergstrom, Demuth, & Braden, 1987). Copyright 1987 by B. Braden and B. Bergstrom. Reprinted with permission.

model, which serves as the theoretical basis for the Braden Scale, purports that PIs result from the interplay of compressive forces (pressure) and compromised tissue tolerance. In the Braden Scale, the pressure component is reflected in three subscales (mobility, activity, and sensory perception) and tissue tolerance is reflected in the remaining subscales (moisture, friction/shear, and nutrition). The authors of the conceptual framework pointed out that some variables impacting tissue tolerance and pressure are not accounted for in the Braden Scale itself, and that those variables are still important in the etiology of PI development (Braden & Bergstrom, 1987).

Table 3.1 identifies all of the variables we sought to include in the current study and the relationship between study variables and Braden and Bergstrom's (1987) conceptual model. Table 3.1 also notes which variables were selected based on the literature and which variables were recommended for inclusion by various clinician groups.

Data Procurement

A quality specialist at University Hospital helped the research team identify fields in the hospital's electronic health record (EHR) system (PowerChart, 2016) corresponding to each variable. When the investigator and quality specialist were unable to locate a variable in the EHR, we contacted end-user clinicians for assistance. We identified fields in PowerChart (2016) corresponding to most of the variables listed in Table 3.1 (we were unable to obtain screen shots for surgical variables; we provided that information in PDF format). We documented the fields by capturing screen shots and other relevant information, including general location within the EHR, and any clinically similar terms. We used these materials to prepare a data request for the research data

Table 3.1

Predictor Variables

Variable & Operational Definition	Rationale	Source
	Conceptual Model Domain: Pressure	
Admission type: emergent	Time spent on an emergency department gurney is time on a suboptimal surface	Clinician input: wound nurses
Admission weight and height (calculate body mass index)	Underweight confers risk due to bony prominence	Literature search
Confusion assessment method: measures delirium	Hypoactive delirium is associated with immobility	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses
Glaslow Coma Scale: measures level of consciousness	Decreased level of consciousness is associated with decreased sensory response to pressure	Literature search
Riker score (sedation scale)	Decreased level of consciousness is associated with decreased sensory response to pressure	Literature search; clinician input: critical-care nurses
Position in bed: critical-care unit	Duration of interface pressure	Literature search; clinician input: critical-care nurses
Positioning: surgery	Duration of interface pressure	Clinician input: surgical nurses
Transport prior to admission	Transport surfaces are suboptimal	Clinician input: wound nurses
Treatment: backboard, cervical collar	Immobility	Literature search
	Conceptual Model Domain: Tissue Tolerance	
Age (in years)	Aging-related physiologic changes decrease tolerance to pressure	Literature search
Arterial blood gas values	Indicates oxygen delivery to tissue, anaerobic metabolism	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses
American Society of Anesthesiologists (ASA) score	Measure of illness severity	Literature search
Braden Scale subscale scores	Risk assessment scale	Literature search

Table 3.1 (Continued)

Variable & Operational Definition	Rationale	Source
Conceptual Model Domain: Tissue Tolerance (Continued)		
Blood pressure	Adequate blood pressure is necessary to deliver oxygen to tissues	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses
Change in weight	Change in weight is an indirect measure of skin status related to edema and potentially third-spacing fluids	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses
Diagnosis (primary and comorbid)	Indicates physiologic status	Literature search
Laboratory values:		Literature search
Albumin (mg/dL) Prealbumin (mg/dL)	Albumin and prealbumin are sometimes used as crude indicators for colloid nutrition status (this is controversial).	
Creatinine (mg/dL)	Creatinine is an indicator of renal failure.	
Glucose (mg/dL)	Excessive glucose is associated with inflammation.	
Hemoglobin (g/dL)	Hemoglobin is a marker of oxygen-carrying capacity.	
Lactate (mg/dL)	Lactate is an indicator of anaerobic metabolism.	
Mechanical ventilation	Indirect marker of respiratory distress and/or severity of illness	Literature search
Organ system failure	It is possible that skin (as an organ system) "fails" as a part of multisystem organ failure.	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses
Prior pressure injury	May indicate skin compromise, particularly if scar tissue developed due to loss of elasticity	Clinician input: wound nurses
Risk of mortality score	Indirect measure of illness severity	Clinician input: anesthesia providers
Severity of illness score	Measure of illness severity	Literature search

Table 3.1 (Continued

Variable & Operational Definition	Rationale	Source
Conceptual Model Domain: Tissue Tolerance (Continued)		
Skin status (nursing assessment includes edema, redness, turgor, overall condition)	Altered skin integrity confers risk for pressure injury	Literature search; clinician input: wound nurses
Surgical factor: duration	Anesthesia is associated with altered perfusion	Clinician input: anesthesia, surgical nursing
Surgical factor: blood pressure, oxygenation, vasopressor infusion during surgery	Altered perfusion during anesthesia	Clinician input: anesthesia, surgical nursing
Surgical factor: temperature (pre-, post-, and during surgery)	Cold temperature causes peripheral vasoconstriction	Clinician input: anesthesia, surgical nursing
Stool output (number of stools/ day)	Moisture from stool predisposes to pressure injury	Literature search
Temperature (°C)	Altered perfusion with hypothermia and hyperthermia	Literature search; clinician input: wound nursing
Tobacco use (smoking yes/no)	Impaired oxygenation and perfusion	Literature search
Treatments: Extracorporeal membrane oxygenation Intra-aortic balloon pump Ventricular assist device	Impaired perfusion	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses
Vasopressor infusion	Peripheral vasoconstriction	Literature search, clinician input: anesthesia providers, intensivist physicians, critical-care nurses
Vital signs: Blood pressure Oxygen saturation	Oxygenation and perfusion	Clinician input: anesthesia providers, intensivist physicians, critical-care nurses

service at the University of Utah.

We requested the data from the University of Utah's Center for Clinical and Translational Science Biomedical Informatics Core's Research Data Service (RDS). The RDS processes requests for data extracts from the University of Utah's Enterprise Data Warehouse (EDW). RDS access to the warehouse is obtained through the EDW via database objects, including views and tables. Most of the views were created by the EDW data administrators over time in an effort to organize data from a number of older and proprietary health record systems. When the views and tables are not able to provide data needed for research objectives, the RDS will query EDW tables directly.

Data Discovery Process

We discussed the data request for this project with the RDS team and provided front-end information (screen shots, locations; see Table 3.1). The RDS team initially determined that the data could be obtained with moderate difficulty; however, the RDS team also indicated that the variables required for this project were extremely difficult to access (see Chapter 7 for a more comprehensive discussion related to our experience in capturing nursing data specifically). Data needed for many variables were not available in warehouse views and had to be obtained using a time-consuming direct search of EDW tables.

Data from the University's PowerChart (2016) system that are not available in views are contained in a single "clinical event" table. This table is a catch-all for clinical data, billing-related data, and other data that have been retained but not yet indexed. The sheer volume of data contained in a single table meant that searching for an individual variable would require hours of query run time in order to find a suitable identifier—if

the identifier could be located at all. After an identifier was found, a time-intensive query process was needed to actually access the clinical data. When the data were finally produced, they were presented to the research team for validation. The research team (JA) validated the data by manually comparing the values and date/time stamps found in the extracted data to those displayed in the human-readable system views for 30 cases, including 15 cases with PI and 15 cases without. We repeated the discovery process if the values and/or date time stamps were not 100% consistent with the human-readable system. A variable was considered complete if, upon implementing the fully developed query for all manually validated cases, we found consistent values and date/time stamps.

Unfortunately, we were not able to locate and therefore extract data for a total of 12 variables; for four additional variables, we were able to obtain data but were unable to obtain data that met our criteria for valid data. Table 3.2 identifies the procurement and validation procedures for all of the variables we attempted to obtain. Variables that were most problematic in terms of validation were from data that nurses produced: positioning information, skin care treatments, and nursing skin assessments. This is unfortunate, because it resulted in a limitation in our ability to build a maximally comprehensive predictive model. A discussion of the implications of difficulty in accessing nursing data is presented in Chapter 7. We were ultimately unable to obtain valid diagnosis information, as the diagnosis information came from billing codes (*ICD* 9 and 10) that did not necessarily reflect the patient's clinical status on a given day.

Table 3.2

Data Procurement and Validation

Variable	Able to Locate in PowerChart? Yes/No	Validation Procedure	Valid Data Obtained? Yes/No
Admission type: emergent	No	N/A	No
First available weight and height (calculate body mass index)	Yes	We attempted validation on results from three distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 data points matched with date/ time stamps within 1 hr.	Yes
Age	Yes	We attempted validation on results from two distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 values matched.	Yes
Arterial blood gas values	Yes	Arterial blood gas values were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes
American Society of Anesthesiologists (ASA) score	Yes	We attempted validation on results from three distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 values matched. Other validation: 18 participants had two ASA scores recorded on a given date. The investigator (JA) used clinical data to manually ascertain the most appropriate ASA score.	Yes
Braden Scale subscale scores	Yes	We attempted validation on results from four distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 values matched We deleted 60 records that included the result "in error" in the "result_status_cd_ display" after determining that those were values nurses deleted due to erroneous entry.	Yes
Blood pressure	Yes	Blood pressure values were validated with 30/30 observations matching the human-readable system with date/time stamps	Yes

Table 3.2 (Continued)

Variable	Able to Locate in PowerChart? Yes/No	Validation Procedure	Valid data obtained? Yes/No
Blood pressure (continued)		accurate +/- 10 minutes in the first query attempt.	
Change in weight	Yes	We obtained daily weight data in two different data sets but we were unable to obtain valid data with 30/30 observations matching the human-readable system.	No
Confusion assessment method	Yes	Confusion-assessment-method values were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes
Diagnosis (primary and comorbid)	Yes	We were able to obtain diagnosis data (*ICD*-9 and -10 codes) but were not able to validate them because the billing data did not reflect clinical events in some cases. For example, one patient who was admitted for a respiratory event had a billing code related to liver failure, despite no clinical evidence of this. *ICD*-9 and -10 codes were not included in the clinician/front-end PowerChart view, so we had no way to directly validate the data value by value.	No
Glaslow Coma Scale	Yes	Glaslow Coma Score values were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes
Laboratory values: Albumin Creatinine Glucose Hemoglobin Lactate Prealbumin	Yes	Laboratory values were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes
Length of stay in ICU	Yes	We attempted validation on results from two distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 values matched.	Yes

Table 3.2 (Continued)

Variable	Able to Locate in PowerChart? Yes/No	Validation Procedure	Valid data obtained? Yes/No
Mechanical ventilation	Yes	We obtained mechanical ventilation data in two different data sets but were unable to obtain valid data with 30/30 observations matching the human-readable system.	No
Organ-system failure	No	We attempted to obtain diagnosis information from billing codes (*ICD*-9 and -10), as noted above. We were unable to obtain specific information about organ-system failure.	No
Position in bed: critical-care unit	No	N/A	No
Positioning: surgery	No	N/A	No
Riker score (sedation scale)	Yes	Riker values were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes
Risk of mortality score	Yes	We obtained risk-of-mortality data in two different data sets but were unable to obtain valid data with 30/30 observations matching the human-readable system.	No
Severity-of-illness score	No	N/A	No
Skin status (nursing assessment included edema, redness, turgor, overall condition)	No	N/A	No
Surgical factor: duration	Yes	We attempted validation on results from two distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 values matched.	Yes
Surgical factor: blood pressure, oxygenation, vasopressor infusion during	No	N/A	No

Table 3.2 (Continued)

Variable	Able to Locate in PowerChart? Yes/No	Validation Procedure	Valid data obtained? Yes/No
Surgical factor: blood pressure (etc.) surgery			
Surgical factor: temperature (pre-, post-, and during surgery)	No	N/A	No
Stool output	No	N/A	No
Temperature	Yes	Temperature values (excepting intraoperative) were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes
Tobacco use (smoking)	No	N/A	No
Transport prior to admission	No	N/A	No
Treatment: backboard, cervical collar	No	N/A	No
Vasopressor infusion	Yes	We attempted validation on results from three distinct queries before we obtained a valid data set. Human-readable system validation: Data were considered valid when 30/30 values matched *We were able to confirm whether a drug was an active order on a given day; we did not have the dose or a time stamp.	Yes*
Vital signs: Blood pressure Oxygen saturation	Yes	Vital sign values (excepting intraoperative) were validated with 30/30 observations matching the human-readable system with date/time stamps accurate +/- 10 minutes in the first query attempt.	Yes

Data Analysis

Braden Scale Study

We used time-dependent survival analysis to determine the hazards of developing a PI based on the total Braden Scale and each Braden subscale. We chose time-varying Cox regression to take into account all of the Braden Scale measurements, assuming that the hazard of developing a PI changes in synchrony with the Braden Scale changes. For each subscale and for the total Braden Scale score, the lowest risk category represented the reference. In addition, we used time-dependent Cox regression with natural cubic splines to model the association of developing a PI with age, by the total Braden Scale score and also by each Braden subscale category. We performed the analysis using statistical software STATA 13, and the statistical significance level was defined at alpha = 0.05.

Predictive Model

We used a random forest (RF) approach to develop a model to predict PI development among critical-care patients. First, we investigated correlations among variables. Next, we looked for patterns of missingness to evaluate whether data were missing completely at random. We determined that the data were not missing at random; therefore, we utilized multiple imputation, an approach that imputes missing values while allowing for a degree of uncertainty (Li, Stuart, & Allison, 2015).

We trained an RF algorithm using the imputed predictor variable data and determined the best number of features to be used for each tree (where M = total number of features and m = best number of features for each tree, $m = \sqrt{M}$). We also determined the optimal number of iterations (or trees in the forest) by choosing the value wherein the

estimated out-of-bag error rate was sufficiently stabilized. Finally, after applying RF to rank variable importance, we put top-performing variables in a logistic model to assess directionality.

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CHAPTER 4

RISK FACTORS FOR PRESSURE INJURIES AMONG CRITICAL-CARE PATIENTS: A SYSTEMATIC REVIEW

Abstract[•]

Our objective with this review was to identify risk factors independently predictive of pressure injury (PI; also known as pressure ulcer) development among critical-care patients. We undertook a systematic review of primary research based on standardized criteria set forth by the Institute of Medicine. We searched the following databases: CINAHL (EBSCOhost), the Cochrane Library (Wilson), Dissertations & Theses Global (ProQuest), PubMed (National Library of Medicine), and Scopus. There was no language restriction. A research librarian coordinated the search strategy. Articles that potentially met inclusion criteria were screened by two investigators. Among the articles that met selection criteria, one investigator extracted data and a second investigator reviewed the data for accuracy. Based on a literature search, we developed a tool for assessing study quality using a combination of currently available tools and expert input. We used the method developed by Coleman and colleagues in 2014 to

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generate evidence tables and a summary narrative synthesis by domain and subdomain. Of 1753 abstracts reviewed, 158 were identified as potentially eligible and 18 fulfilled eligibility criteria. Five studies were classified as high quality, two were moderate quality, nine were low quality, and two were of very low quality. Mobility/activity, age, and vasopressor infusion emerged as important risk factors for PI development, whereas results for risk categories that are theoretically important, including perfusion (apart from vasopressor infusion), nutrition, and general health status, were mixed. Methodological limitations across studies limited the generalizability of the results, and future research is needed, particularly to elucidate risk conferred by altered nutrition, perfusion, and skin/PI status. The results underscore the importance of avoiding overinterpretation of a single study, and the importance of taking study quality into consideration when reviewing risk factors. Maximal PI prevention efforts are particularly important among critical-care patients who are older, who have altered mobility, or who are receiving a vasopressor infusion.

Introduction

Hospital-acquired pressure injuries (HAPIs; formerly called pressure ulcers) are localized areas of damage to the skin, underlying tissue, or both, as a result of pressure. HAPIs occur in 3% to 34% of hospitalized patients worldwide and result in longer hospital stays, increased morbidity, and increased human suffering.[1-4]

Due to negative outcomes associated with PIs, standards of practice include a recommendation to conduct PI risk assessment and comprehensive skin assessment upon admission and at any time there is a significant change in a patient's condition.[5] Accurate risk assessment along with comprehensive skin assessment enables prompt recognition

and treatment of PIs that occur among high-risk patients, which is important because early (category 1) pressure injuries are highly treatable[6]; however, discernment of which individuals are at highest risk for PIs in the intensive care unit (ICU) is problematic because the risk-assessment scales currently used for critical-care patients tend to identify almost all patients as "high risk."[7]

Critical-care patients represent a highly specialized patient population, and risk for PIs in this population is likely to be different than risk in other populations, particularly as it relates to perfusion and general skin status due to severity of illness and treatments, including vasopressor infusion, that are unique to critical-care patients.[8] The purpose of the current review is to identify factors that are independently associated with increased risk for PIs among critical-care patients specifically. An independent risk factor retains its statistical association with the outcome variable when other risk factors are included in the model; note that independence is a statistical concept and does not imply causality.[9,10]

We evaluated identified independent risk factors in relation to clinical relevance and in relation to recent PI conceptual and theoretical frameworks.[5,11] We also evaluated risk factors in relation to study quality, as a recent PI study conducted in a general population determined that most of the included studies were of low or very low quality.[9]

Methods

Research Protocol

We undertook a systematic review of primary research. Our approach was based on the standardized criteria set forth by the Institute of Medicine[12] for comparative effectiveness reviews and modified to appraise risk-factor/observational studies.[9]

Eligibility Criteria

We adapted inclusion criteria based on the method employed by Coleman and colleagues,[9] to include *(a)* primary research; *(b)* adult sample; *(c)* ICU setting; *(d)* prospective cohort, retrospective record review, or controlled trial; and *(e)* identification of independent risk factors for PI (multivariate analysis). Exclusion criteria included the following: *(a)* limited to pediatric patient population (age <18 years), *(b)* >25% of the study population were excluded from analysis due to loss to follow up or missing records, *(c)* prevalence or cross-sectional study, *(d)* limited to evaluation of a PI risk-assessment scale, and *(e)* limited to spinal cord injury (SCI) patients (due to the specialized physiology involved in SCIs and the associated risk for PI among individuals with SCI.[13] There was no language restriction.

Search Strategy

We searched the medical subject headings *pressure injury* and *intensive care units* in addition to field-restricted keywords for the following databases: CINAHL (EBSCOhost), the Cochrane Library (Wilson), Dissertations & Theses Global (ProQuest), and PubMed (National Library of Medicine). We downloaded our final results on December 17, 2016. A complete description of the search is outlined in Tables 4.1 and 4.2.

Data Extraction

Two investigators (JA and LB) identified potentially eligible studies. Among those deemed potentially eligible, JA noted whether each study met inclusion criteria for this review (or stated the reason the study did not meet criteria) and LB checked JA's

Table 4.1

Search Lexicon

Term	Function
MH	Restricts the search to MeSH headings assigned to the article
TI	Keyword search for terms in the article title
tiab	Keyword search for terms in the title or abstract
+	Medical subject heading exploded to include all narrower subject terms
“ ”	Exact phrase search
*	Wildcard - can replace any letter or, at the end of the word, multiple letters
su	ProQuest subject headings

Table 4.2

Search Statements Employed

Database	Search Statement	No. of Results
Medline (EBSCO)	((MH "Pressure Ulcer") OR (TI “pressure ulcer*”)) AND ((MH “intensive care”) OR (MH “intensive care units”) OR (TI intensive care unit*) OR (TI “critical care”))	243
Medline (EBSCO)	((MH "Intensive Care Units+") OR (MH "Critical Care+")) AND (MH "Pressure Ulcer+")	334
PubMed	(pssure injur*[TI] OR pressure ulcer*[TI] OR pressure sore*[TI] OR bed sore*[TI] OR bedsore*[TI] OR decubital ulcer*[TI] OR decubitus ulcer*[TI] OR ulcus decubitus[TI] OR "Pressure Ulcer"[Mesh]) AND ("Critical Care"[Mesh] OR "Intensive Care Units"[Mesh] OR "Burn Units"[Mesh] OR "Coronary Care Units"[Mesh] OR "Intensive Care Units, Pediatric"[Mesh] OR "Intensive Care Units, Neonatal"[Mesh] OR "Recovery Room"[Mesh] OR "Respiratory Care Units"[Mesh] OR "Critical Illness"[Mesh] OR "Critical Care Nursing"[Mesh] OR "Critical Care Outcomes"[Mesh] OR critical care[TI] OR Critically Ill[TI] OR critical ill*[TI] OR intensive care[TI] OR cardiovascular unit*[TI] OR coronary care[TI] OR Cardiac Care[TI] OR neurocritical care[TI] OR neurointensive care[TI] OR step-down unit*[TI] OR step down unit*[TI] OR burn unit*[TI] OR high dependency unit*[TI] OR neurosurgical unit*[TI] OR surgical intensive care[TI] OR Recovery Room*[TI] OR recovery unit*[TI] OR observation unit*[TI] OR observational unit*[TI] OR Respiratory Care[TI] OR ICU[tiab] OR ICUs[tiab] OR NICU[tiab] OR NICUs[tiab] OR CCU[tiab] OR CCUs[tiab] OR SICU[tiab] OR SICUs[tiab])	441
CINAHL (EBSCO)	((MH "Intensive Care, Neonatal+") OR (MH "Intensive Care Units+") OR (MH "Critical Care+") OR (TI "intensive care") OR (TI "critical care")) AND ((MH "Pressure Ulcer+") OR (TI "Pressure Ulcer") OR (TI "Pressure ulcers"))	506
Cochrane	pressure ulcer* AND ("intensive care" unit* OR "intensive care" OR "critical care") in Title, abstract, kw	113
Scopus	pressure ulcer* AND ("intensive care" unit* OR "intensive care" OR "critical care") in Title, abstract, kw	926
Dissertations and Theses	su(pressure ulcer*) AND su((intensive care OR critical care))	9
Dissertations and Theses	diskw(pressure ulcer*) AND diskw((intensive care OR critical care))	8

Note. NLM subject headings: https://www.nlm.nih.gov/mesh/. With regard to database selection: Though the material indexed in Medline is also included in NLM PubMed, the search algorithms can vary between interface providers, as can post-limit features and other options, and thus can yield slightly different results sets.

categorizations. Disagreements were addressed by a third researcher, JR, and agreement was determined by consensus. In addition, one investigator (JA) extracted data pertaining to study design, population, setting, analysis, and results, and a second investigator (JRB) reviewed the data for accuracy.

Quality Appraisal

In an effort to identify a quality-assessment tool for the current review, we conducted a literature search. We determined that no currently available checklists or scales fit closely with the objectives of the current review while offering adequate inter-rater reliability.

We used the available tools to guide development of our tool for assessing quality among PI risk-factor studies. First, the authors of a systematic review of quality-assessment tools for observational studies concluded that available checklists and scales did not differentiate well between poor study reporting and a truly flawed study.[14] The authors recommended that instead of assigning a summative score based primarily on reporting, quality assessment of observational risk-factor studies should be conducted by defining flaws in different domains—an approach that results in more transparent conclusions when compared with global scoring based on a checklist or summative evaluation tool. Similarly, authors of a systematic review of quality-appraisal tools for observational epidemiological studies recommended against summative scores and instead advised an approach based on evaluation of bias in particular quality domains.[15]

The quality-appraisal tool developed for the current review (see Table 4.3) includes the domains identified in Sanderson and colleagues'[15] review of quality appraisal among observational studies: methods for selecting participants, methods for

Table 4.3

Quality Appraisal of Observational Studies of Pressure Injury Risk in Critical Care

Domain	Major Flaws	Moderate Flaws	Indeterminate Flaws
Methods for selecting participants	(More than 25% of sample lost to follow up and missing records were exclusion criteria for the current review.)	≥15% of the population lost to follow up or missing records Restricted sampling, resulting in limited generalizability The study sampled from high-risk patients on a risk-assessment scale and then included the factors in the scale as potential predictor variables; or, very restricted sampling frame that resulted in limited generalizability	Inclusion/exclusion criteria are unclear
Statistical methods and control of confounding	Clearly incorrect statistical methods Inadequate number of events (pressure injuries) for analysis: <10 pressure injuries per variable included in the multivariate analysis[10,43]	Nonindependent factors are included in analysis without appropriate adjustment[10] Time-dependent covariates (e.g., blood pressure) included without appropriate adjustment[10] Selective reporting of results[9] Inappropriate strategy for model building[3] Unclear statistical reporting: • Multivariate statistical significance is only reported for variables deemed significant (for underpowered studies, it is not possible to tell which variables were close and may be significant if the study was adequately powered) • Despite the presence of missing data, the authors do not describe how missing data were handled Problematic statistical methods: • Poor model fit or no reporting of model fit • Significance tests for predictors not reported	Unclear statistical reporting
Methods for measuring exposure	Temporal ambiguity: it is possible that the predictor variable occurred *after* the pressure injury event.	Variable operationalization is unclear or misleading. Incomplete data for predictor variables • Despite the presence of missing data, no description of how missing data were handled; or missing data	No reporting of missing data for predictor variables

Table 4.3 (Continued)

Domain	Major Flaws	Moderate Flaws	Indeterminate Flaws
Methods for measuring exposure (continued)		were handled inappropriately	despite high likelihood of missing data
Methods for measuring outcome variable	No criteria for wound designation as a pressure injury (e.g., NPUAP/ EPUAP ≥category 1 or equivalent)	Nurses who were not wound nurses and not specially trained identified or categorized pressure injuries.	Limited description of the outcome variable (e.g., no staging information)
Conflict of interest	Evidence of conflict of interest, with major implications for study results	Evidence of conflict of interest, with minor implications for study results	Evidence of conflict of interest, with unclear implications for study results

References:

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43. Peduzzi PJ, Concato AR, Feinstein X, Holford TR. Importance of events per independent variable in proportional hazards regression analysis. II. Accuracy and precision of regression estimates. *J Clin Epidemiol*. 1996;48(12):1503-1510.

measuring exposure and outcome variables, design-specific sources of bias, methods to control confounding, statistical methods (excluding control of confounding), and conflict of interest. Major and moderate flaws are noted in each domain in which presence of a major flaw is a significant indicator that the flaw has substantially compromised our confidence in the study conclusions.

Although the quality-appraisal method employed in this study was focused on sources of bias in different domains, we determined that an evaluative descriptor was necessary to facilitate study classification according to the degree of actual or potential bias. Using the rubric provided in Table 4.3, we employed the following evaluation based on specific sources of bias:

1. *High-quality studies* had 0 potential sources of bias with major implications for study quality and ≤1 potential sources of bias with moderate implications for study quality;

2. *Moderate-quality studies* had 1 potential source of bias with major implications for study quality and ≤1 potential sources of bias with moderate implications for study quality; or 0 potential sources of bias with major implications for study quality and 2–3 potential sources of bias with moderate implications for study quality;

3. *Low-quality studies* had 1 potential source of bias with major implications for study quality and 2–4 potential sources of bias with moderate implications for study quality, or 0 potential sources of bias with major implications for study quality and 4–7 potential sources of bias with moderate implications for study quality; and

4. *Very-low-quality studies* had 2 or more potential sources of bias with major implications for study quality, or ≥8 potential sources of bias with moderate implications for study quality.

Indeterminate sources of bias were items that may or may not have introduced bias; indeterminate items were noted but did not count toward the evaluative descriptor category. We sought expert input during tool development, and the final tool reflects consensus among two experts in PI research and one expert in observational research.

Data Synthesis

Meta-analysis was not feasible for this review because of a high degree of clinical heterogeneity related to population, predictor variable operationalization, preventive interventions, and different thresholds for the PI outcome variable (new category 1 and greater PI vs. new category 2 and greater) according to the international National Pressure Ulcer Advisory Panel/European Pressure Ulcer Advisory Panel (NPUAP/EPUAP) classification system.[5] The purpose of the review was to identify risk factors rather than to quantify the effect size of the relationship between a given factor and PI development; therefore, we conducted a narrative synthesis. We utilized the narrative synthesis method previously employed by Coleman and colleagues.[9] We recorded all potential risk factors entered into multivariate analysis and identified the factors that emerged as independent factors for PI risk. For studies using stepwise regression, we included factors that were not statistically significant upon bivariate analysis if those factors were identified as independent risk factors for PIs in the final model.[9] Finally, we categorized recorded risk factors and potential risk factors into domains and subdomains.

Domains were structured according to Coleman and colleagues'[11] interpretation of the NPUAP/EPUAP conceptual framework (see Figure 4.1). Domain 1 encompasses sources of pressure and also friction and shear, which are conceptualized as mechanical boundary conditions rather than as patient characteristics.[11] Domain 2 comprises those factors that influence the susceptibility and tolerance of the individual. Some factors have an effect on mechanical boundary conditions *and* on the susceptibly and tolerance of the individual, and therefore some overlap exists between the two major domains; for

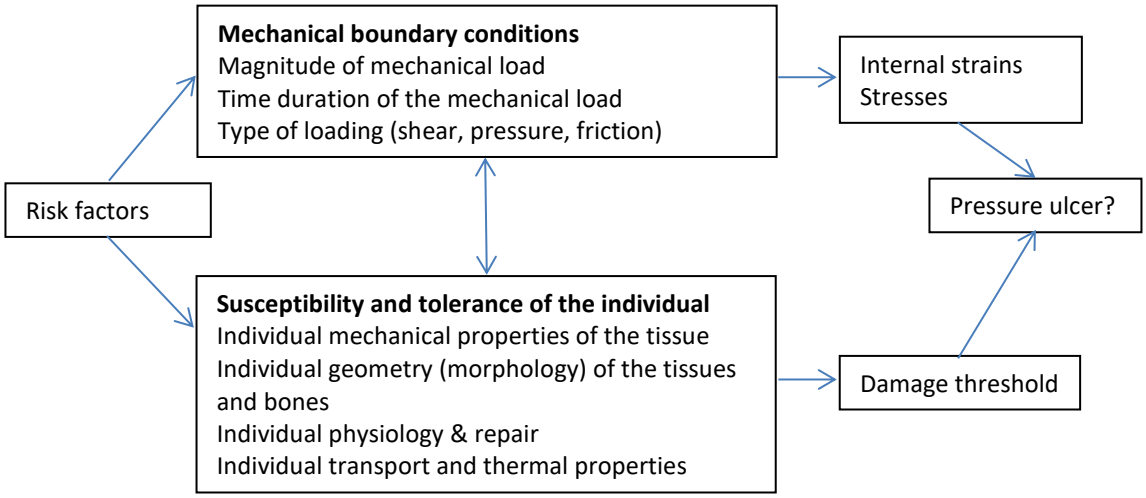

Figure 4.1 Enhancement of NPUAP/EPUAP factors that influence susceptibility for pressure ulcer development (Coleman et al.,[11] p. 2229). Copyright 2014 by S. Coleman. Reprinted with permission.

tolerance and susceptibility through altered perfusion. We developed subdomains in relation to Coleman and colleagues'[11] theoretical schema of a proposed causal pathway for pressure ulcer development (see Figure 4.2), which built upon the NPAUP/EPUAP/Pan Pacific Pressure Injury Alliance conceptual framework[5] and identified immobility, skin and pressure injury status, and poor perfusion as direct causal factors in pressure injury development.[11]

Limitations

Our study was limited to critical-care patients within the ICU setting. Therefore, it is possible that we failed to include research that featured critically ill patients in other settings, or subgroup analysis of studies that featured various levels of acuity among hospitalized patients.

Results

Study Characteristics

Of 1753 abstracts reviewed, 158 were identified as potentially eligible and 18 fulfilled eligibility criteria (see Figure 4.3). The retained studies included 13 prospective cohort and five retrospective record reviews.

Quality Appraisal

Two researchers conducted the quality appraisal and reached "substantial" agreement independently, as evidenced by Kappa = 0.72.[16] After interrater reliability was calculated, the researchers reviewed any discrepancies and came to agreement. When possible, we contacted study authors for clarification purposes.

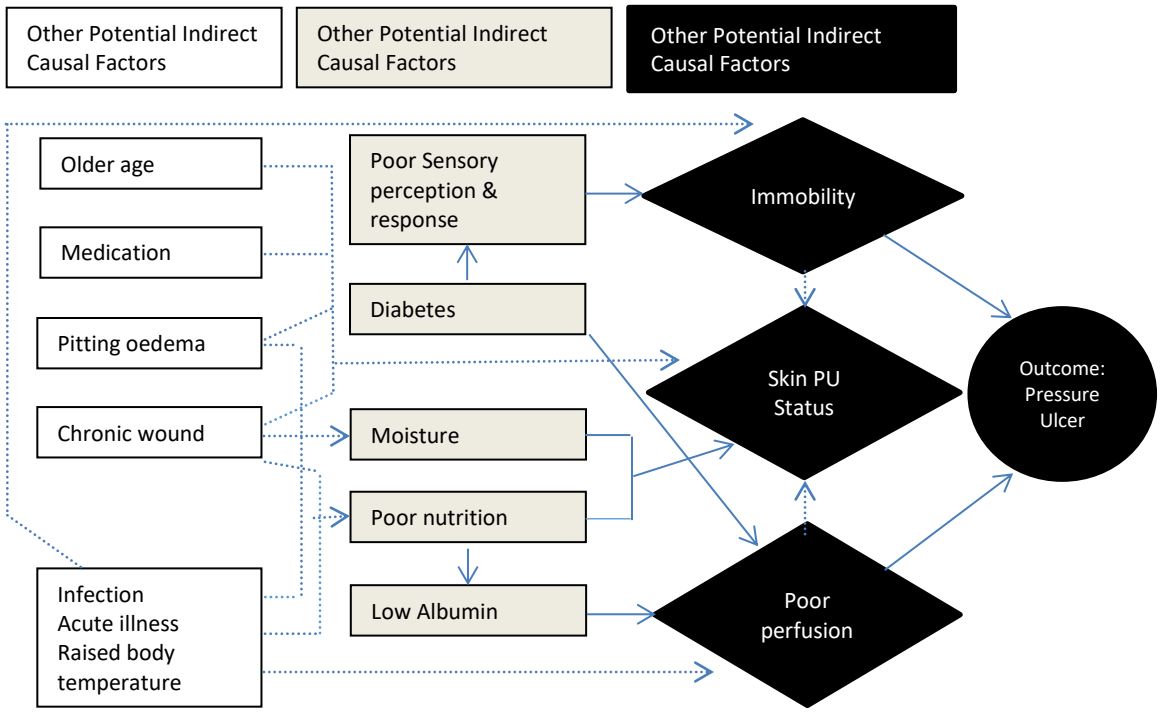

Figure 4.2 Theoretical schema of proposed causal pathway for pressure ulcer development.

Note. The solid arrows show the causal relationship between the key indirect causal factors and the outcome. Interrupted arrows show the causal relationship between other potential indirect causal factors and key indirect causal factors and between direct causal factors. Interrupted arrows also demonstrate interrelationships between direct causal factors and indirect causal factors (Coleman et al.,[11] p. 2229). Copyright 2014 by S. Coleman. Reprinted with permission.

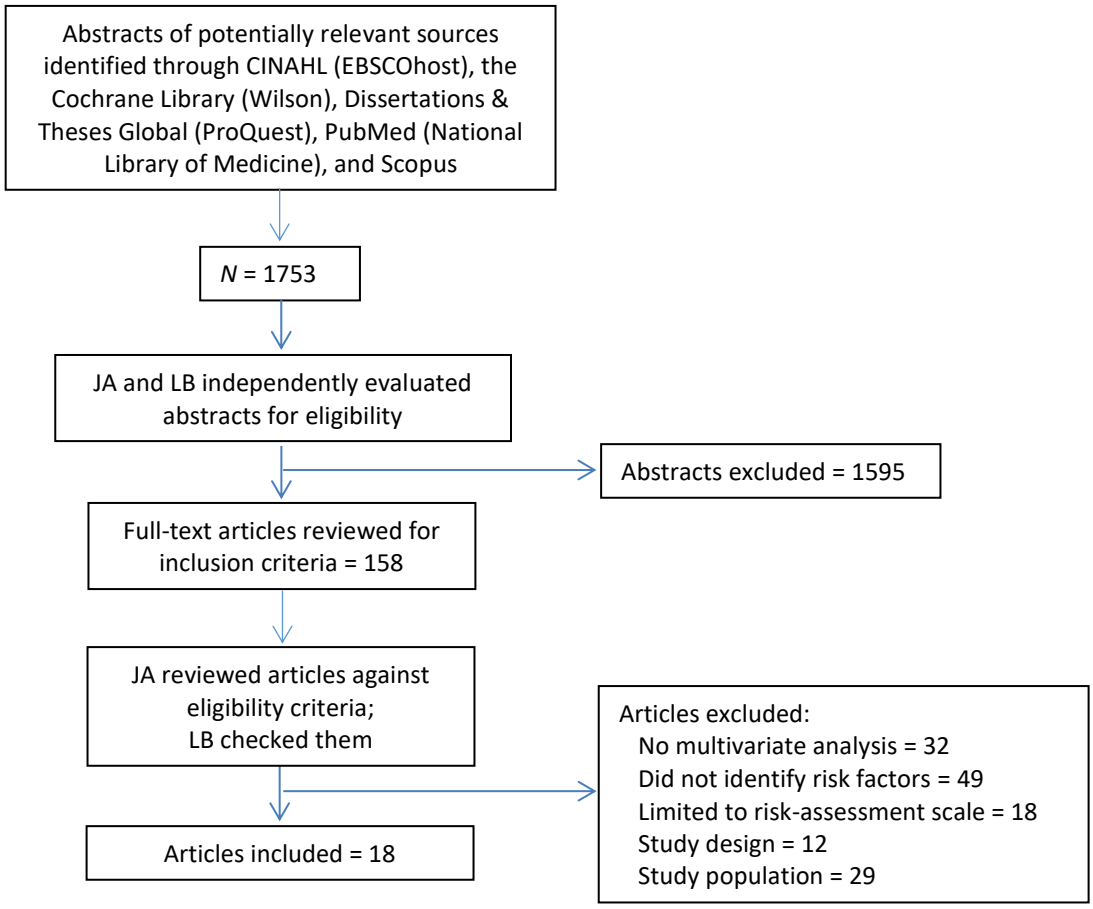

Figure 4.3 Decision process.

Quality appraisal results are identified in Table 4.4. The included studies had between zero and two major sources of bias, and between one and six moderate sources of bias; overall, five studies were classified as high quality,[4,17–20] two were of moderate quality,[21,22] nine were of low quality,[2,23,24,25-30] and two were of very low quality[1,31] (Table 4.4). The methodological limitations we found were similar to other reviews of PI risk-factor studies in the sense that most of the included studies (61%) were of either low quality or very low quality.[7,9] Eleven (64%) of the 17 included studies did not have adequate numbers of PI events for analysis, a limitation that is reflected in some studies in the wide confidence intervals associated with reported odds ratios.

Pressure Injury Outcome Variable

Two of the 18 studies included for review did not describe criteria used to designate a PI.[1,31] Two studies did not report specific PI categories,[1,4] six studies designated a PI as a new injury ≥category 1,[17.18,23–27,30,31] eight studies included only new PIs that were ≥category 2,[2,19,21,22,28–31] and two studies included separate models for PIs ≥category 1 and ≥category 2 (Table 4.5).[20,25]

Risk-Factor Domains and Subdomains

The authors of 14 studies reported all of the risk factors entered into multivariate modeling as well as those that emerged as independently predictive of PI,[2,4,17,19–28,31] whereas authors of three studies reported only the variables that emerged as significant from multivariate modeling.[1,27,29] A summary of risk factors entered into the multivariate model (when available) and those that emerged as independent risk factors are summarized by study and by risk-factor domain (see Table 4.6).[9]

Table 4.4

Study Quality: Potential Bias

Study	Methods for Selecting Participants	Statistical Methods and Control of Confounding	Methods for Measuring Exposure	Methods for Measuring Outcome Variable	Conflict of Interest	Notes and Quality Appraisal
Compton et al.[28]	--	Major: Inadequate number of events for analysis Moderate: Unclear statistical reporting	--	Moderate: Nurses who were not specially trained identified PIs	--	LQS Strength: Used an independent cohort to validate model
Cox[31]	--	Note on events for analysis: The author included a power analysis indicating there were enough events.	--	Moderate: Nurses who were not specially trained identified PIs	--	HQS
Cox & Roche[17]	--	--	--	--	--	HQS
Cremasco et al.[1]	--	Major: Inadequate number of events for analysis Moderate: Unclear statistical reporting Moderate: Non-independent factors included in the analysis without appropriate adjustment	--	Major: No criteria for designation of wound as a PI Moderate: Nurses who were not specially trained identified PIs Moderate: Limited description of the outcome variable	--	VLQS

Table 4.4 (Continued)

Study	Methods for Selecting Participants	Statistical Methods and Control of Confounding	Methods for Measuring Exposure	Methods for Measuring Outcome Variable	Conflict of Interest	Notes and Quality Appraisal
Eachempati et al.[31]	Moderate: Restricted sampling (included	Major: Clearly incorrect statistical	--	Major: No criteria for designation of wound	--	VLQS
Eachempati et al.[31] (continued)	only patients with LOS>6 days) Moderate: Unclear inclusion/ exclusion criteria	methods Moderate: Inappropriate strategy for model building		as a PI Moderate: Nurses who were not specially trained identified PIs Moderate: Limited description of the outcome variable		
Fife et al.[22]	--	Major: Inadequate number of events for analysis Moderate: Unclear statistical reporting	--	Moderate: Limited description of the outcome variable	--	LQS
Frankel et al.[2]	Indeterminate: Individuals appear to have been excluded from the study but the inclusion/exclu-sion criteria are not defined	Major: Inadequate number of events for analysis	--	Moderate: Nurses who were not specially trained identified PIs	--	LQS
Kaitani et al.[23]	--	Major: Inadequate number of events for	Moderate: Variable operation is unclear	--	--	LQS

Table 4.4 (Continued)

Study	Methods for Selecting Participants	Statistical Methods and Control of Confounding	Methods for Measuring Exposure	Methods for Measuring Outcome Variable	Conflict of Interest	Notes and Quality Appraisal
Kaitani et al.[23] (continued)		analysis Moderate: >15% lost to follow up or missing records/inadequate data collection Moderate: Inappropriate strategy for model building				
Manzano et al.[21]	--	Major: Inadequate number of events for analysis	Indeterminate: No reporting of missing data for predictor variables despite high likelihood of missing data	--	--	MQS
Nijs et al.[22]	--	Major: Inadequate number of events for analysis Moderate: Problematic statistical methods with moderate implications for study findings	Indeterminate: Potential temporal ambiguity (it is possible that the predictor variable occurred after the pressure injury event)	--	--	MQS
O'Brien et al.[22]	--	--	--	Moderate: Nurses who were not specially trained identified PIs	--	HQS

Table 4.4 (Continued)

Study	Methods for Selecting Participants	Statistical Methods and Control of Confounding	Methods for Measuring Exposure	Methods for Measuring Outcome Variable	Conflict of Interest	Notes and Quality Appraisal
Sayar et al.[24]	--	Moderate: Sampled from "high-risk" patients on a risk-assessment scale and then included attributes of the same scale as predictor variables	Moderate: Non-independent factors are included in the analysis without proper adjustment Moderate: Selective reporting of results Moderate: Unclear statistical reporting	--	--	LQS
Slowikowski & Funk[4]	--	--	--	Moderate: Limited description of the outcome variable	--	HQS
Suriadi et al.[18]	--	--	Moderate: Unclear statistical reporting	--	--	HQS
Tayyib et al.[25]	--	Major: Inadequate number of events for analysis Moderate: Nonindependent factors included in the analysis without appropriate adjustment	--	Moderate: Nurses who were not specially trained identified PIs	--	LQS
Theaker et al.[26]	--	Major: Inadequate number of events for analysis	--	Moderate: Nurses who were not specially trained identified PIs	--	LQS

Table 4.4 (Continued)

Study	Methods for Selecting Participants	Statistical Methods and Control of Confounding	Methods for Measuring Exposure	Methods for Measuring Outcome Variable	Conflict of Interest	Notes and Quality Appraisal
Theaker et al.[26] (continued)		Moderate: >15% lost to follow up or missing records Moderate: Nonindependent factors included in the analysis without appropriate adjustment		Moderate: Limited description of the outcome variable		
Ulker Efteli & Yapucu Gunes[27]	Moderate: Restricted sampling	Major: Inadequate number of events for analysis	--	Moderate: Nurses who were not specially trained identified PIs	--	LQS
Ulker Efteli & Yapucu Gunes[27] (continued)	(included only patients with LOS>6 days)		--			
Yepes et al.[30]	Moderate: Restricted sampling (included only patients on mechanical ventilation and vasopressor support)	Moderate: Nonindependent factors included in the analysis without appropriate adjustment Moderate: Unclear statistical reporting	--	Moderate: Nurses who were not specially trained identified PIs	--	

Note. PI = pressure injury/-ies; LQS = low-quality study; HQS = high-quality study; VLQS = very-low-quality study; LOS = length of stay; LQS = low-quality study.

Table 4.5

Summary of Studies

Study Authors	Sample and Country	Inclusion Criteria	Design and Analysis	No. in Final Model (PI%), No. of PI and Category	Results: No. of Risk Factors (No. in Model); Model Risk-Factor Names: Odds Ratio (95% CI)	Study Quality
Compton et al.[28]	713 general ICU patients in Germany	≥72-hr stay No PI upon admission	Retrospective record review Logistic regression	698 (17%), 121 Categories 2–4	32 (6) Male gender: 1.8 (NR) Moist skin: 2.4 (NR) Edematous skin: 2.2 (NR) Centralized circulation: 2.4 (NR) Mottled skin: 2.0 (NR) Reddened skin: 2.3 (NR)	MQS
Cox[11]	347 medical–surgical ICU patients in the United States	≥24-hr stay No PI upon admission Age ≥18 years	Retrospective record review Logistic regression	Model 1: 347 (18.7%), 65 ≥category 1 Model 2: 327 (13.7%), 45 ≥category 2	Model 1: 15 (4) Mobility: 0.439 (0.21–0.95) Age: 1.033 (1.003–1.064) Length of ICU stay: 1.008 (1.005–1.011) Cardiovascular disease: 2.952 (1.3–6.4) Model 2: 15 (4) Friction/shear: 5.715 (1.423–22.95) Length of ICU stay: 1.008 (1.004–1.012) Norepinephrine: 1.017 (1.001–1.033) Cardiovascular disease: 3.380 (1.223–9.347)	HQS
Cox & Roche[17]	306 medical, surgical, and cardiothoracic ICU patients in the United States	≥24-hr stay No PI upon admission Age ≥18 Received a vasopressor during ICU stay	Retrospective record review Logistic regression	306 (13%), 41 ≥category 1	11 (5) Cardiac arrest: 3.894 (0.998–15.118) Mechanical ventilation ≥72 hr: 23.604 (0.998–15.118) Hours of MAP less than 60 mm HG while on vasopressors: 1.096 (1.020–1.178) Vasopressin: 4.816 (1.666–13.925) Cardiac diagnosis at admission: 0.035 (0.002–	HQS

Table 4.5 (Continued)

Study Authors	Sample and Country	Inclusion Criteria	Design and Analysis	No. in Final Model (PI%), No. of PI and Category	Results: No. of Risk Factors (No. in Model); Model Risk-Factor Names: Odds Ratio (95% CI)	Study Quality
Cox & Roche[17] (continued)					0.764)	
Cremasco et al.[1]	160 modical–surgical ICU patients in three ICUs in Brazil	≥24-hr stay No PI upon admission	Prospective cohort Logistic regression	160 (34.4%), 55, category not reported	NR (4) Male gender: 5.4 (1.42–22.09) Length of ICU stay: 1.120 (1.943–1.202) SAPSI score: 1.058 (1.004–1.114) NAS score: 0.916 (0.855–0.980)	LQS
Eachempati et al.[31]	Phase 2: 412 surgical ICU patients in the United States	Length of stay>7 days	Prospective cohort Logistic regression	55 (60%), 33≥category 2	7 (5) Emergent admission: 36 (0.2290–0.7694) Age: -0.0131) Days in bed: 1.05 (-0.0013–0.0156) CURS day 8: 1.45 (-0.0048–-0.0833) Days without any nutrition: 0.51 (-0.1095–-0.0334)	VLQS
Fife et al.[29]	186 neurologic ICU patients in the United States	No PI upon admission No diagnosis of brain death on life support pending organ donation	Prospective cohort Logistic regression	186 (12%), 23≥category 2	NR (2) Braden score: NR (NR) Low body mass index (BMI): NR (NR)	MQS
Frankel et al.[2]	820 surgical ICU patients in the United States	Not reported	Retrospective record review Logistic regression	820 (3%), 25≥category 2	9 (4) Diabetes: 2.7 (1.1–6.4) Age: 2.9 (1.2–7.1) Creatinine: 3.7 (1.2–9.2)	MQS

Table 4.5 (Continued)

Study Authors	Sample and Country	Inclusion Criteria	Design and Analysis	No. in Final Model (PI%), No. of PI and Category	Results: No. of Risk Factors (No. in Model); Model Risk-Factor Names: Odds Ratio (95% CI)	Study Quality
Frankel et al.[2] (continued)					Spinal cord injury: 16.8 (1.5–182)	
Kaitani et al.[23]		Age≥20 years No PI upon admisison ≥24-hr stay	Prospective cohort Logistic regression	98 (11.2%), 11 categories 1–4	6 (2) Scheduled admission: 0.04 (0–0.47) Frequency of turning: 0.45 (0.21–0.97)	LQS
Kaitani et al.[23] (continued)	98 ICU and high-care-unit patients in Japan	Unable to make major and frequent position changes independently				
Manzano et al.[21]	299 patients in nine ICUs in Spain	Mechanical ventilation Age≥18 years Nonpregnant	Prospective cohort Logistic regression	299 (15.7%), 47≥category 2	16 (5) Day 1 respiratory SOFA: 1.56 (1.026–2.360) Day 4 cardiovascular SOFA: 1.33 (1.066–1.664) Age: 1.042 (1.013– 1.072) Winter: 4.6 (1.99–10.59) Length of mechanical ventilation: 1.042 (1.005–1.080)	HQS
Nijs et al.[22]	520 surgical ICU patients in Belgium	Age≥16 years ≥24-hr expected stay Absence of burns	Prospective cohort Logistic regression	463 (28.9%), 134 categories 2–4	19 (9) Dopamine <5 mcg/kg/min: 6.1 (1.9–19.5) Vascular disease: 4.5 (2.0–10.2) Dialysis: 3.8 (1.0–13.9) “Adequate prevention”: 6.0 (1.9–18.6) Frequency of turning six or more times daily	HQS

Table 4.5 (Continued)

Study Authors	Sample and Country	Inclusion Criteria	Design and Analysis	No. in Final Model (PI%), No. of PI and Category	Results: No. of Risk Factors (No. in Model); Model Risk-Factor Names: Odds Ratio (95% CI)	Study Quality
Nijs et al.[22] (continued)					or alternating mattress: 30.2 (12.2–74.8) "Turning": 6.7 (2.7–16.4) Sedative use: 0.3 (0.1–0.7) Body temperature≤38.5: 0.2 (0.2–0.9) Sitting in chair: 0.1 (0.0–0.3)	
O'Brien et al.[19]	2695 surgical and burn ICU patients in the United States	Age≥18 years ≥48-hr ICU stay Underwent a surgical procedure No pressure injury	Retrospective record review	2695 (10.7%), 288 category≥2	12 (7) Existing airway: 5.28 (3.63–7.67) Low BMI: 2.7 (1.45–5.04) Noncardiac surgery: 1.84 (1.31–2.59) History of heart failure: 1.78 (1.27–2.49) History of renal failure: 1.75 (1.27–2.39)	HQS
O'Brien et al.[19] (continued)		upon admission			ASA class 4 or 5: 1.63 (1.19–2.29) Age: 1.02 (1.01–1.03)	
Sayar et al.[24]	140 medical–surgical ICU patients in Turkey	At risk or at high risk on Waterlow pressure ulcer risk scale	Prospective cohort Logistic regression	140 (14.3%), 20 category≥1	5 (2) Length of stay: 1.2 (1.1–1.3) Activity level: 0.3 (.02–0.7)	MQS
Slowikowski & Funk[4]	369 surgical ICU petients in the United States	Age≥16 years	Prospective cohort Logistic regression	369 (23.9%), 88, category not reported	8 (3) Braden Scale score: 1.3 (1.15–1.47) Diabetes: 1.93 (1.11–3.35) Age≥70 years: 2.14 (1.27–3.62)	HQS
Suriadi et al.[18]	253 general ICU patients in Indonesia	Age≥18 years Bedfast No PI upon	Prospective cohort Logistic	253 (28.4%), 72≥category 1	NR (3) Interface pressure: 2.2 (1.6–2.9) Body temperature: 2.0 (1.7–2.5)	HQS

Table 4.5 (Continued)

Study Authors	Sample and Country	Inclusion Criteria	Design and Analysis	No. in Final Model (PI%), No. of PI and Category	Results: No. of Risk Factors (No. in Model); Model Risk-Factor Names: Odds Ratio (95% CI)	Study Quality
Suriadi et al.[18] (continued)		admission ≥24-hr stay and anticipated stay≥72 hr	regression		Cigarette smoking: 1.6 (1.1–2.5)	
Tayyib et al.[25]	84 general ICU patients in Saudi Arabia	Age≥18 years	Prospective cohort	84 (39.3%), 33 categories 1–4	Model 1 Categories 1–4: 7 (3) Age: 1.254 (1.054–1.492) Longer ICU stay: 1.23 (1.014–3.309) Infrequent repositioning: 250.04 (230–11,954.16) Model 2 Categories 2–4: 3 (2) Longer ICU stay: 1.831 (1.054–1.492) Infrequent repositioning: 2.96 (1.23–7.153)	MQS
Theaker et al.[26]	286 general ICU patients in the United Kingdom	>24-hr stay No PI upon admission Three or more PI risk factors	Prospective cohort Logistic regression	286 (26.9%), 77 categories 2–4	18 (5) Norepinephrine infusion: 8.11 (3.64–18) APACHE II≥13: 2.4 (1.4–7.92) Fecal incontinence: 3.27 (1.32–8.3) Anemia: 2.81 (1.24–6.34) Length of stay≥three days: 2.76 (1.06–7.05)	LQS
Ulker Efteli & Yapucu Gunes[27]	70 general ICU patients in Turkey	Age≥18 years Expected ICU stay≥7 days No PI upon admission Braden Scale score<12	Prospective cohort Logistic regression	70 (33%), 23≥category 1	6 (2) Female gender: 0.15 (0.03–0.71) Lower serum albumin level: 11.6 (1.92–70.4)	MQS

Table 4.5 (Continued)

Study Authors	Sample and Country	Inclusion Criteria	Design and Analysis	No. in Final Model (PI%), No. of PI and Category	Results: No. of Risk Factors (No. in Model); Model Risk-Factor Names: Odds Ratio (95% CI)	Study Quality
Yepes et al.[30]	150 ICU patients in Bolivia	Intubated On mechanical ventilation Received vasopressor	Prospective cohort Logistic regression	150 (26.7%), 40≥category 2	3 (3) Presence of infection: 4.39 (6.92–18.25) Length of stay in the ICU: 1.13 (1.06–1.22) APACHE II: 1.06 (1.0–1.12)	LQS

Note. PI = pressure injury; CI = confidence interval; ICU = intensive care unit; NR = not reported; MQS = moderate-quality study; HQS = high-quality study; MAP = mean arterial pressure; LQS = low-quality study; SAPSI = Simplified Acute Physiology Score; NAS = nursing activities score; VLQS = very-low-quality study; CURS = Corneil ulcer risk score; SOFA = sequential organ failure assessment; ASA = American Society of Anesthesiologists; APACHE = acute physiology and chronic health evaluation.

Table 4.6

Summary of Evidence for Risk-Factor Domains and Subdomains

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
	Domain 1: Mechanical Boundary Conditions	
Body size	--	MQS (Manzano et al.[21]) Body weight LQS (Compton et al.[28]) Body weight and height
Friction and shear	HQS (Cox[20]) Friction/shear: 5.715 (1.423–22.95)	--
Emergent vs. scheduled admission	LQS (Kaitani et al.[23]) Scheduled admission: 0.04 (0–0.47) VLQS (Eachempati et al.[31]) Emergent admission: 36 (0.2290–0.7694)	HQS (O'Brien et al.[19]) Emergent admission MQS (Manzano et al.[21]) Type of admission (medical vs. surgical) LQS (Tayyib et al.[25]) Emergent admission LQS (Kaitani et al.[23]) Admission type
	Domain 1 Subdomain: Immobility	
Mental/neurologic status	--	MQS (Nijs et al.[22]) GCS: opens eyes MQS (Nijs et al.[22]) GCS: movement, localizes pain MQS (Nijs et al.[22]) GCS: movement, follows commands LQS (Compton et al.[28]) Minimum GCS LQS (Compton et al.[28]) Maximum GCS LQS (Sayar et al.[24]) Consciousness LQS (Sayar et al.[24]) Cooperation LQS (Theaker et al.[26]) Pain
Mobility/activity	HQS (Cox[20]) Mobility: 0.439 (0.21–0.95) LQS (Sayar et al.[24]) Activity level: 0.3 (0.2–0.7)	--
Sensory perception	--	HQS (Cox[20]) Sensory perception

Table 4.6 (Continued)

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
Surgical factors	HQS (O'Brien et al.[19]) Noncardiac surgery: 1.84 (1.31–2.59)	LQS (Tayyib et al.[25]) Operation time
Turning/repositioning and surface	HQS (Suriadi et al.[18]) Interface pressure: 2.2 (1.6–2.9) MQS (Nijs et al.[22]) "Adequate prevention": 6.0 (1.9–18.6) MQS (Nijs et al.[22]) Frequency of turning six or more times daily or alternating mattress: 30.2 (12.2–74.8) MQS (Nijs et al.[22]) "Turning": 6.7 (2.7–16.4) MQS (Nijs et al.[22]) Sitting in chair: 0.1 (0.0–0.3) LQS (Tayyib et al.[25]) Infrequent repositioning: 2.96 (1.23–7.153) LQS (Kaitani et al.[23]) Frequency of turning: 0.45 (0.21–.0.97)	HQS (Slowikowski & Funk[4]) Not repositioned LQS (Theaker et al.[26]) Too unstable to turn
	Domain 2: Susceptibility and Tolerance of the Individual	
Age	HQS (Cox[20]) Age: 1.033 (1.003–1.064) HQS (O'Brien et al.[19]) Age: 1.02 (1.01–1.03) HQS (Slowikowski & Funk[4]) Age≥70 years: 2.14 (1.27–3.62) MQS (Frankel et al.[2]) Age: 2.9 (1.2–7.1) LQS (Tayyib et al.[25]) Age: 1.254 (1.054–1.492) VLQS (Eachempati et al.[31]) Age: 1.08 (0.0026–0.0131)	MQS (Manzano et al.[21]) Age
Body temperature	HQS (Suriadi et al.[18]) Body temperature: 2.0 (1.7–2.5) MQS (Nijs et al.[22]) Body temperature≥38.5: 0.2 (0.2–0.9)	LQS (Compton et al.[28]) Maximum body temperature
Diagnosis* * (excepting diagnosis related to oxygenation and perfusion, included	HQS (O'Brien et al.[19]) History of renal failure: 1.75 (1.27–2.39) LQS (Frankel et al.[2]) Spinal cord injury: 16.8 (1.5–182) LQS (Yepes et al.[30]) Presence of infection: 4.39 (6.92–	HQS (O'Brien et al.[19]) History of liver disease MQS (Manzano et al.[21]) Multiple organ failure MQS (Nijs et al.[22]) Gastrointestinal diagnosis LQS (Tayyib et al.[25]) History of kidney disease

Table 4.6 (Continued)

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
Diagnosis (continued) below under Subdomain: Poor Perfusion)	18.25)	
Laboratory values (excepting values related to oxygenation and perfusion, included below under Subdomain: Poor Perfusion)	LQS (Frankel et al.[2]) Creatinine: 3.7 (1.2–9.2) LQS (Theaker et al.[26]) Anemia: 2.81 (1.24–6.34)	HQS (Cox & Roche[17]) Severe anemia LQS (Compton et al.[28]) Maximum serum potassium LQS (Compton et al.[28]) Maximum creatinine LQS (Compton et al.[28]) Maximum blood glucose LQS (Compton et al.[28]) Maximum c-reactive protein LQS (Compton et al.[28]) Minimum thromboplastin time LQS (Compton et al.[28]) Maximum serum bilirubin LQS (Ulker Efteli & Yapucu Gunes[27]) Hemoglobin LQS (Ulker Efteli & Yapucu Gunes[27]) Blood glucose LQS (Sayar et al.[24]) C-reactive protein LQS (Theaker et al.[26]) Coagulopathy
Length of stay	HQS (Cox[20]) Length of ICU stay: 1.008 (1.005–1.011) LQS (Sayar et al.[24]) Length of stay: 1.2 (1.1–1.3) LQS (Tayyib et al.[25]) Longer ICU stay: 1.831 (1.014–3.309) LQS (Yepes et al.[30]) Length of stay: 1.13 (1.06–1.22) LQS (Theaker et al.[26]) Length of stay > 3 days: 2.76 (1.08–7.05) VLQS (Cremasco et al.[1]) Length of ICU stay: 1.120 (1.943–1.202) VLQS (Eachempati et al.[31]) Days in bed: 1.05 (-0.0013–0.0156)	HQS (Cox & Roche[17]) Hospital length of stay HQS (Cox & Roche[17]) Length of stay before ICU admission HQS (Cox & Roche[17]) ICU length of stay MQS (Manzano et al.[21]) ICU length of stay MQS (Manzano et al.[21]) Pre-ICU hospital stay LQS (Compton et al.[28]) Duration of ICU stay
Medication (excepting vasopressors) and	MQS (Nijs et al.[22]) Sedative use: 0.3 (0.1–0.7) MQS (Nijs et al.[22]) Dialysis: 3.8 (1.0–3.9)	HQS (O'Brien et al.[19]) Current corticosteroid use HQS (Slowikowski & Funk[4]) Orthotics

Table 4.6 (Continued)

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
Medication (continued) treatments		HQS (Slowikowski & Funk[4]) Hemodialysis MQS (Nijs et al.[22]) Physical fixation MQS (Nijs et al.[22]) Major analgesics MQS (Nijs et al.[22]) "Floating heels" LQS (Compton et al.[28]) Sedation LQS (Compton et al.[28]) Insulin therapy LQS (Theaker et al.[26]) Current corticosteroid use
Nutrition and laboratory values related to nutrition status	LQS (Ulker Efteli & Yapucu Gunes[27]) Lower serum albumin level: 11.6 (1.92–70.4) VLQS (Eachempati et al.[31]) Days without any nutrition 0.51 (-0.1095–-0.0334)	HQS (Cox[20]) Nutrition LQS (Compton et al.[28]) Parenteral nutrition LQS (Kaitani et al.[23]) Nutrition LQS (Theaker et al.[26]) Serum albumin LQS (Theaker et al.[26]) Reduced nutritional intake
Severity of illness/health status	HQS (Cox & Roche[17]) Cardiac arrest: 3.894 (0.998–15.118) HQS (O'Brien et al.[19]) ASA class 4 or 5: 1.63 (1.19–2.23) MQS (Manzano et al.[21]) Day 1 respiratory SOFA: 1.56 (1.026–2.360) MQS (Manzano et al.[21]) Day 4 cardiovascular SOFA: 1.33 (1.066–1.664) LQS (Yepes et al.[30]) APACHE II: 1.06 (1.0–1.12) LQS (Theaker et al.[26]) APACHE II> 13: 2.4 (1.4–7.92) VLQS (Cremasco et al.[1]) SAPSII score: 1.058 (1.004–1.114)	HQS (Cox[20]) APACHE HQS (Cox & Roche[17]) APACHE II HQS (Cox & Roche[17]) Died in ICU MQS (Manzano et al.[21]) Hospital mortality MQS (Nijs et al.[22]) APACHE II LQS (Ulker Efteli & Yapucu Gunes[27]) APACHE II LQS (Compton et al.[28]) ICU mortality LQS (Compton et al.[28]) TISS LQS (Kaitani et al.[23]) APACHE II LQS (Theaker et al.[26]) Peripheral vascular disease VLQS (Eachempati et al.[31]) MODS VLQS (Eachempati et al.[31]) APACHE III

Domain 2 Subdomain: Skin/Pressure Injury Status
Including Factors That Affect Skin and Pressure Injury Status

Table 4.6 (Continued)

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
Moisture	LQS (Compton et al.[28]) Moist skin: 2.4 (NR)	LQS (Theaker et al.[26]) Moisture
Skin/external skin factors/ PI status	LQS (Compton et al.[28]) Edematous skin: 2.2 (NR) LQS (Compton et al.[28]) Centralized circulation: 2.4 (NR) LQS (Compton et al.[28]) Mottled skin: 2.0 (NR) LQS (Compton et al.[28]) Reddened skin: 2.3, (NR) LQS (Theaker et al.[26]) Fecal incontinence: 3.27 (1.32–8.3)	HQS (Cox & Roche[17]) Peripheral necrosis in patients receiving vasopressors HQS (Slowikowski & Funk[4]) Edema MQS (Nijs et al.[22]) Pitting edema LQS (Compton et al.[28]) Livid skin LQS (Compton et al.[28]) Hyperemic skin LQS (Kaitani et al.[23]) Edema LQS (Theaker et al.[26]) Edema
	Domain 2 Subdomain: Poor Perfusion *Including Factors That Affect Oxygenation and Perfusion Status/Delivery of Oxygen to the Tissues*	
Diagnosis related to oxygenation and/or perfusion (also included in global diagnosis, above)	HQS (Cox[20]) Cardiovascular disease: 2.952 (1.3–6.4) HQS (Cox & Roche[17]) Cardiac diagnosis at admission: 0.035 (0.002–0.764) HQS (O'Brien et al.[19]) History of heart failure: 1.78 (1.27–2.49) HQS (Slowikowski & Funk[4]) Diabetes: 1.93 (1.11–3.35) HQS (Suriadi et al.[18]) Cigarette smoking: 1.6 (1.1–2.5) MQS (Nijs et al.[22]) Vascular disease: 4.5 (2.0–10.2) LQS (Frankel et al.[2]) Diabetes: 2.7 (1.1–6.4)	HQS (O'Brien et al.[19]) History of diabetes MQS (Manzano et al.[21]) Septic shock MQS (Manzano et al.[21]) Acute respiratory distress syndrome LQS (Frankel et al.[2]) Vascular disease LQS (Compton et al.[28]) Sepsis LQS (Tayyib et al.[25]) History of cardiovascular disease LQS (Theaker et al.[26]) Diabetes LQS (Theaker et al.[26]) History of smoking
Oxygenation/laboratory values related to oxygenation	HQS (Cox & Roche[17]) mechanical ventilation longer than 72 hr: 23.604 (6.427-86.668) HQS (O'Brien et al.[19]) existing airway: 5.28 (3.63-7.67) MQS (Manzano et al.[21]) length of mechanical ventilation: 1.042 (1.005–1.080)	HQS (Slowikowski & Funk[4]) Ventilator support MQS (Manzano et al.[21]) Pa02/Fi02 ratio on Day 1 MQS (Nijs et al.[22]) Mechanical ventilation LQS (Compton et al.[28]) Minimum PaCO2 LQS (Compton et al.[28]) Minimum arterial pH LQS (Compton et al.[28]) Mechanical ventilation

Table 4.6 (Continued)

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
Oxygenation/laboratory values related to oxygenation (continued)		LQS (Compton et al.[28]) Cyanosis LQS (Tayyib et al.[25]) Mechanical ventilation
Perfusion/laboratory values related to perfusion	HQS (Cox & Roche[17]) Hours of MAP less than 60 mm HG while on vasopressors: 1.096 (1.020–1.178)	HQS (Cox[20]) Mean arterial pressure HQS (Cox[20]) Systolic blood pressure HQS (Cox[20]) Diastolic blood pressure LQS (Compton et al.[28]) Maximum heart rate LQS (Compton et al.[28]) Invasive monitoring
Vasopressor	HQS (Cox[20]) Norepinephrine: 1.017 (1.001–1.033) HQS (Cox & Roche[17]) Vasopressin infusion: 4.816 (1.666–13.925) MQS (Nijs et al.[22]) Dopamine<5 mcg/kg/min: 6.1 (1.9–19.5)	LQS (Compton et al.[28]) Vasopressor therapy LQS (Frankel et al.[2]) Vasopressor therapy LQS (Theaker et al.[26]) Dopamine LQS (Theaker et al.[26]) Epinephrine
Vasopressor (continued)	LQS (Theaker et al.[26]) Norepinephrine infusion: 8.11 (3.64–18)	LQS (Theaker et al.[26]) Norepinephrine
	Other Factors Not Included In Domains 1 or 2	
Gender	LQS (Ulker Efteli & Yapucu Gunes[27]) Female gender: 0.15 (0.03–0.71) LQS (Compton et al.[28]) Male gender: 1.8 (NR) VLQS (Cremasco et al.[1]) Male gender: 5.6 (1.42–22.09)	LQS (Kaitani et al.[23]) gender G
Risk-assessment scales	HQS (Slowikowski & Funk[4]) Braden Scale score: 1.3 (1.15–1.47) LQS (Fife et al.[29]) Braden Scale score: NR (NR) VLQS (Eachempati et al.[31]) CURS Day 8: 1.45 (-0.0048– -0.0833)	HQS (Cox[20]) Braden Scale total HQS (Cox & Roche[17]) Braden Scale at hospital admission HQS (Cox & Roche[17]) Braden Scale at ICU admission LQS (Compton et al.[28]) Waterlow score LQS (Tayyib et al.[25]) Braden Scale score

Table 4.6 (Continued)

Variable	Studies With Variable Significant in Multivariate Model Study Quality (Study Authors) Variable: Odds Ratio (95% CI)	Studies With Variable Not Significant in Multivariate Model Study Quality (Study Authors) Variable
Other factors	MQS (Manzano et al.[21]) Winter admission: 4.6 (1.99–10.59) VLQS (Cremasco et al.[1]) NAS score: 0.916 (0.855–0.980)	--

Adapted from Coleman et al.[9]

Note. CI = confidence interval; HQS = high-quality study; MQS = moderate-quality study; LQS = low-quality study; VLQS = very-low-quality study; GCS = Glaslow Coma Scale; APACHE = Acute Physiology and Chronic Health Evaluation ; TISS = trauma injury severity score; MODS = multiple organ dysfunction syndrome; PA02/FI02 = ratio of arterial oxygen partial pressure to fractional inspired oxygen; PaCO2 = carbon dioxide partial pressure; MAP = mean arterial pressure; CURS = Corneil ulcer risk score; NAS = nursing activities score; PI = pressure injury.

Domain 1: Mechanical Boundary Conditions

Mechanical boundary conditions are aspects that influence the magnitude of the mechanical load, the time duration, and also the type of loading (pressure, friction, shear; Figure 4.1).[5] We extended this category to include body size because of the potential for increased mechanical load due to bony prominence among underweight individuals. We also included emergent admission because emergency department gurneys have a suboptimal surface,[32] and surgical time as time in surgery confers immobility.

Body Size

One moderate-quality study[21] and one low-quality study[28] included body size in the multivariate analysis, but neither weight nor height emerged as significant upon multivariate analysis (Table 4.5). No study included change in weight, however, which might have been useful for assessing fluid shifts. Additionally, no study included a height/weight composite such as body mass index, which would have indicated underweight or excessive adipose tissue.

Friction and Shear

Recent developments in PI research indicate that friction-induced skin injuries are not true PIs, whereas shearing forces cause a decrease in regional blood flow and therefore are important in PI risk.[33,34] Authors of only one study[20] entered a shear-related variable into multivariate modeling; the study, which was of high quality, found that friction/shear (as defined by the Braden Scale[35]) was independently predictive of pressure injury development (Table 4.5).

Emergent Versus Scheduled Admission

We included emergent admission in Domain 1 because time in the emergency department is associated with time spent on suboptimal surfaces such as gurneys.[32] Five study authors entered admission type into their statistical model.[18,19,21,23,25] In two of those studies (33%),[23,31] emergent admission was found to be independently predictive for PI development; however, the two studies were of low- and very-low quality.

Domain 1 Subdomain: Immobility

Within Domain 1, Coleman and colleagues'[11] schema depicts immobility as a direct causal factor (Figure 4.2). Therefore, factors associated with this subdomain are presented below.

Mental/Neurologic Status

Researchers in four studies,[22,24,26,28] including one moderate-quality study[22] and three low-quality studies,[24,26,28] entered variables related to neurologic status into multivariate analysis. No variables related to mental status emerged in multivariate analysis (Table 4.3).

Mobility/Activity

One high-quality study[20] and one low-quality study[24] each identified mobility and activity level, respectively, as independently predictive of PIs (Table 4.3).

Sensory Perception

Sensory perception was entered into the statistical model of one high-quality study but did not emerge as an independent risk factor.[20]

Surgical Factors

Information pertaining to surgical factors was limited. One high-quality study[19] found that undergoing noncardiac surgery was an independent risk factor for PI, whereas one low-quality study[25] entered operative time into the multivariate model, but it did not emerge as an independent risk factor (Table 4.3).

Turning/Repositioning and Surface

Overall, authors of six studies entered one or more turning- and/or repositioning-related variables into the statistical model[4,23,18,22,25-28]; one study entered four variables related to positioning[22] (Table 4.3). Results were conflicting. In their moderate-quality study, Nijs and colleagues[22] found that *more frequent* turning was an independent risk factor for PI development, whereas two low-quality studies[23,25] each found that *less frequent* repositioning was independently predictive of PI risk (Table 4.3). Nijs and colleagues speculated that perhaps high-risk patients experienced enhanced nursing vigilance in turning and repositioning.[22]

Domain 2: Susceptibility and Tolerance of the Individual

Domain 2 includes factors that influence the susceptibility and tolerance of the individual (Figure 4.1). Subdomains within Domain 2 are skin/PI status, which includes existing and previous PIs and general skin status, and poor perfusion, which encompasses conditions that alter oxygen delivery to the tissues.[11]

Body Temperature

Three studies,[18,22,28] including one of high quality, one of moderate quality, and one of low quality, included body temperature in multivariate analysis, with conflicting

results. The high-quality study found that fever was an independent risk factor for PI development[18]; the moderate-quality study found that fever was a protective factor,[22] and in the low-quality study,[28] fever did not emerge as significant in multivariate analysis (Table 4.2).

Diagnosis Not Directly Related to Oxygenation and Perfusion

Renal failure and high creatinine were each determined to be independent risk factors for PI development in one high-quality study[19] and one low-quality study,[2] respectively. Researchers in one high-quality[4] and one moderate-quality study[22] entered dialysis into multivariate modeling. In the moderate-quality study, dialysis was independently predictive of PI development, whereas dialysis did not emerge as an independent risk factor in the high-quality study. Serum creatinine was independently predictive of PI development in one low-quality study[2] (Table 4.3).

Laboratory Values

Researchers in six studies,[2,17,24,26–28] including one high-quality study, entered laboratory values into multivariate analysis (apart from albumin, which is discussed under "Nutrition," and blood-gas values, which are included in the oxygenation results; see Table 4.2). Only two laboratory values were statistically significant upon multivariate analysis: creatinine was an independent risk factor in one low-quality study,[2] and anemia emerged in one low-quality study.[26]

Length of Stay

Length of stay (LOS) independently predicted risk for PI development in seven[1,20,24,25,26,30,31] of the 11 studies that included LOS in multivariate analysis (Table

4.2).[1,17,20,21,24–26,28,30,31,35] Only one study,[21] however, differentiated LOS *prior* to PI development, which is important, because development of a PI increases the length of a hospital stay.[36]

Medications

Among five studies that included medications other than vasopressors,[4,19,22,26,28] one moderate-quality study[22] found that sedative use was an independent risk factor for PI development (Table 4.3).

Nutrition

In the current review, only one low-quality study determined that a nutrition-related variable (serum albumin) was independently predictive of PI risk.[27] Four other studies evaluated nutrition-related variables,[20,23,26,28] but nutrition did not emerge as predictive in multivariate modeling (Table 4.3). Of note, one very-low-quality but frequently cited study indicated that days without nutrition was an independent risk factor for PI development[31]; in that study, however, the data presented in tables and the associated odds ratio indicate the opposite: that days without nutrition was a *protective* factor. That paradoxical finding was actually replicated in the bivariate analysis conducted by Slowikowski and Funk,[4] but the authors did not enter nutrition in the multivariate analysis because they thought it might have been a spurious finding.

Severity of Illness/Health Status

Eight studies included the Acute Physiology and Chronic Health Evaluation (APACHE) score as a marker of severity of illness in their multivariate model,[17,20,22,23,26,27,30,31] and two low-quality studies[26,30] identified the APACHE score as

predictive of PI risk (Table 4.2). The APACHE score is calculated using measurements that occur within 24 hr after admission, and the score is not repeated; therefore, the APACHE may not be a sensitive indicator of severity of illness throughout a several-day hospital course.[37] Furthermore, experts contend that the APACHE should be used primarily to provide performance comparisons between ICUs rather than to provide an assessment of an individual patient's illness severity.[37]

Among other markers of illness severity, an American Society of Anesthesiologists (ASA) Class 4 or Class 5 score was an independent risk factor for PIs in one high-quality study,[19] and sequential organ failure assessments on Days 1 and 4 were also independent risk factors for PIs in a moderate-quality study[21] (Table 4.3). Hospital and/or ICU mortality were considered in one high-quality study[17] and two moderate-quality studies,[21,28] but mortality did not emerge as statistically significant in the multivariate model.

Domain 2 Subdomain: Skin/Pressure Injury Status

The subdomain of skin and PI status includes existing and previous PIs and general skin status. Skin/PI status is included in Coleman and colleagues'[11] conceptual schema as a direct causal factor in PI development (Figure 4.2).

Moisture

Moisture is included in skin/PI status due to its close relationship with skin condition.[38]Two studies evaluated moisture,[26,28] and it emerged as an independent risk factor for PI in one moderate-quality study[28] (Table 4.3).

External Skin Factors

Researchers in six studies entered variables related to skin status into multivariate modeling.[4,17,22,23,26,28] The variables included external conditions (incontinence), assessment of the skin's appearance, and edema (Table 4.2). Edema emerged from multivariate modeling in one low-quality study,[28] but was not independently predictive of PI risk in one high-quality study,[4] one moderate-quality study,[22] and two low-quality studies.[23,26] Peripheral necrosis due to vasopressor use was not an independent predictor of PI in one study.[17] A single study recorded detailed examination of the skin's condition[28]; that low-quality study found that centralized circulation, mottled skin, and reddened skin were independent predictors of PI development, whereas livid skin and hyperemic skin did not emerge from the multivariate analysis (Table 4.2).

Domain 2 Subdomain: Poor Perfusion

The subdomain of poor perfusion includes factors that alter oxygen delivery to tissues. Poor perfusion is included in Coleman and colleagues' conceptual schema as a direct causal factor in PI development.[11]

Diagnosis Related to Oxygenation and/or Perfusion

Researchers in 10 studies entered diagnoses related to potentially altered perfusion (including diabetes, cardiovascular disease, and peripheral vascular disease) into multivariate modeling,[2,4,17–22,25,28] and the diagnoses emerged as independent risk factors in five,[4,17–19,22] including four high-quality studies[4,17,19,20] and one moderate-quality study[22] (Table 4.2). Researchers in two studies included sepsis, another condition resulting in altered tissue perfusion, in their multivariate modeling, but sepsis did not

emerge as a significant risk factor.[21,28] In addition, researchers in two studies entered cigarette smoking into multivariate modeling[18,26]; smoking was an independent risk factor for PI development in the study by Suriadi et al.[18]

Oxygenation

Authors of seven studies entered oxygenation-related variables into multivariate modeling[4,17,19,21,22,25,28]; among those, one high-quality[17] and one moderate-quality study[21] identified length of mechanical ventilation as independently predictive of PI risk. Other oxygenation-related variables did not emerge as independently predictive (Table 4.3); however, variable operationalization limits the generalizability of the findings: only two studies included blood-gas results, and both studies limited their data collection to the first 24 hr.[21,28] Furthermore, mechanical ventilation may be more indicative of severity of illness than oxygenation status because a patient could be stable from a respiratory standpoint but still require mechanical ventilation support due to other disease processes.

Perfusion

In a high-quality study conducted among individuals receiving vasopressors,[17] more hr with a mean arterial pressure of less than 60 mm Hg was independently predictive of PIs (Table 4.3). Two additional studies included perfusion-related variables[20,28]; however, variable operationalization limits the generalizability of the findings. First, Cox defined blood pressure as the total number of hours in the first 48 hr that the patient had a mean arterial pressure <60 mm Hg, and/or systolic blood pressure <90 mm Hg, and/or diastolic blood pressure <60 mm Hg.[20] In Cox's study, the mean

length of stay was five days, and therefore blood pressure readings were not recorded for more than half of a typical patient's ICU stay.[20] Compton and colleagues also collected data pertaining to perfusion; however, they recorded perfusion-related variables only for the first 24 hr of hospitalization, despite inclusion criteria specifying at least a 72-hr ICU stay.[28]

Vasopressors

Vasopressor infusion is commonly administered to critical-care patients to improve perfusion in shock states, with resulting peripheral vasoconstriction, which may confer risk for PI.[20] Authors of six studies entered a vasopressor variable into multivariate analysis,[2,17,20,22,26,28] and in four of those studies, including two high-quality studies,[17,20] vasopressor infusion emerged as independently predictive of PI development[17,20,22,26] (Table 4.3). In their high-quality study, Cox and Roche found that patients receiving vasopressin were at increased risk for PI development.[17] Variable operationalization contributed to difficulty comparing across studies. Cox[20] and Cox and Roche[17] recorded hours of administration of specific vasopressor agents and hour/dose, respectively, whereas Nijs and colleagues[22] recorded dose but not duration of vasopressor infusion and Theaker et al.[26] dichotomized norepinephrine infusion as "yes/no."

Other Factors Not Included in Domains 1 and 2

Gender

Four studies included gender in the multivariate model,[1,23,27,28] and in three of the four,[1,27,28] male gender was independently predictive of PI risk.

Risk-Assessment Scales

Overall, seven studies included a risk-assessment-scale total score in their multivariate analysis,[4, 17,20,25,28,29,31] and in three studies (43%),[4,29,31] the total score emerged as an independent risk factor (Table 4.3). The total score for the Braden Scale[39] emerged in one high-quality study[4] and one low-quality study,[29] and did not emerge in two high-quality studies[17,20] and one low-quality study.[25]

Other Factors

A high-quality study found winter season was a risk factor for PI development.[21] Researchers in one low-quality study noted that increased nursing workload was a slightly protective factor.[1]

Discussion

Our findings reveal inconsistent results among studies, as well as marked variability in study quality, indicating that researchers should avoid overinterpretation of results from any single study. Each study was subjected to quality assessment, which will allow clinicians and researchers to take quality into consideration when evaluating results.

In the current review of PI risk factors among critical-care patients, activity/ mobility and age frequently emerged as important factors in PI development, which is consistent with the results from a systematic review conducted by Coleman and colleagues in an acute, rehabilitative, long-term-care population.[11] The finding that mobility is an important subdomain is in keeping with current theoretical knowledge, given that mobility is a direct causal factor in Coleman and colleagues' conceptual

model.[11] However, results for other domains that are conceptualized as important, direct causal factors, including perfusion and skin/PI status, were mixed.

The unexpectedly inconsistent results for variables including perfusion and skin/PI status may be attributed to methodological limitations. Perfusion is a dynamic process, particularly among critical-care patients, who are at risk for hemodynamic instability. Only one study[17] incorporated perfusion-related measures throughout the patient's entire ICU stay; other studies that included perfusion-related variables utilized cut points that presented dynamic hemodynamic processes as dichotomous variables, an approach that fails to quantify the magnitude of hypotension. Similarly, only one study recorded the duration of hypotension.[17]

Vasopressor agents are an important element influencing perfusion among ICU patients, but are difficult to study due to variability in effects on peripheral circulation related to dose delivered and receptors targeted. Among studies in the current review, only one study[17] included the dose of the vasopressor for the entire duration of administration, and the same study was the only one to capture the potentially synergistic effects of more than one vasopressor agent. Despite methodological limitations, however, results from the current review indicate that vasopressor agents are important in PI development. Among two high-quality studies and one moderate-quality study that examined various vasopressor-related variables, all found that vasopressors were independent predictors.[17,20,22]

Cox and Roche[17] examined a population receiving vasopressor therapy and found increased risk among individuals receiving vasopressin, which is important because vasopressin is typically considered a second-line drug and is commonly administered

along with norepinephrine for vasodilatory shock.[40] This is particularly interesting in light of a prevalence study conducted by Bly and colleagues[35] that determined that infusion of more than one vasopressor conferred risk for P.• Additional research is needed to elucidate the effects of individual vasopressor agents, the potentially synergistic effects of multiple agents (particularly concomitant use of norepinephrine and vasopressin), and the underlying effects of the shock state that the vasopressor agents treat.

Coleman and colleagues' conceptual model indicates that skin and PI status are direct causal factors in PI development.[11] The conclusion that skin status is important is also supported by current clinical practice guidelines and by the broader PI literature.[5] Unfortunately, however, information pertaining to skin and PI status in the current review was extremely limited; only one study addressed skin status (excepting edema) throughout the hospitalization (vs. only on admission).[17] Additionally, the authors of 10 (56%) of the 18 studies in the current review excluded patients who were admitted to the ICU with a preexisting PI, which is unfortunate, because individuals with proven skin compromise are therefore not represented in more than half of the included studies.[1,17–20,23,26-29]

Although nutrition is theoretically a factor in PI development, results from the current review failed to demonstrate a connection between nutrition status and PI development among critical-care patients. Eachempati and colleagues' study concluded that more days without nutrition conferred risk for PIs; however, careful analysis of their study shows the opposite.[31] In Table 4 on page 1681, the 33 patients with a PI were

• The study by Bly et al.[35] was a prevalence study, and therefore did not meet inclusion criteria for the current review.

shown to have experienced a mean of 1.9 days without nutrition, whereas the 22 patients without a PI experienced a mean of 4.3 days without nutrition. Furthermore, the reported odds ratio of 0.51 indicates a protective effect.[31] In their high-quality study, Slowikowski and Funk[4] also found that patients receiving no nutrition had a lower incidence of PI, but they chose not to enter nutrition in multivariate analysis because they were concerned that it was a spurious finding, citing Eachempati and colleagues'[31] erroneous conclusion that days without nutrition conferred risk. In the future, researchers should utilize more sensitive nutrition indictors. Guidance on appropriate measurement of nutrition status among critical-care patients is available from the American Society for Parenteral and Enteral Nutrition in coordination with the Society of Critical Care Medicine.[41]

In addition to poor perfusion, skin/PI status, and nutrition, more information is needed about the relationship between surgery and the risk for PI development. A high-quality retrospective record review of 3225 surgical patients (not limited to critical care) found that multiple surgeries and total surgical time were independent risk factors for PI development.[42] Only two studies in the current review included surgical factors in multivariate analysis.[19,25]

Conclusion

Results from this review of PI risk factors among critical-care patients underscore the importance of avoiding overinterpretation of a single study, and the importance of taking study quality into consideration when reviewing risk factors. Mobility/activity, age, and vasopressor infusion emerged as important risk factors for PI development, whereas results for risk categories that are theoretically important, including perfusion (apart from vasopressor infusion), skin and PI status, and nutrition, were mixed.[5]

Methodological limitations across studies limit generalizability of results, and future research is needed, particularly to elucidate risk conferred by altered perfusion, vasopressor infusion, nutrition, and skin and PI status. Clinicians may consider extending maximal preventive interventions to critical-care patients who are older, who experience altered mobility/activity, or who receive vasopressor infusions. Future research examining the effects of nutrition, altered perfusion, and especially skin and PI status, is needed.

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CHAPTER 5

MIDRANGE BRADEN SUBSCALE SCORES ARE ASSOCIATED WITH INCREASED RISK FOR PRESSURE INJURY DEVELOPMENT AMONG CRITICAL-CARE PATIENTS

Abstract

Hospital-acquired pressure injuries are a serious problem among patients in the intensive care unit (ICU). In the United States, pressure injury (PI) risk and associated care planning have historically been determined using the Braden Scale total score; however, some institutions now use Braden Scale subscale scores to focus pressure injury-prevention efforts. The purpose of the current study was to examine the risk of developing a PI associated with Braden subscale scores in a surgical ICU population, and to ascertain whether the risk represented by the subscale scores is different between older versus younger patients. We identified a cohort of 6376 surgical ICU patients via electronic health record data to determine Braden Scale total and subscale scores, age, and incidence of PI development. We used survival analysis to determine the hazards of developing a PI associated with each subscale of the Braden Scale, with the lowest risk category as a reference. In addition, we used time-dependent Cox regression with natural

cubic splines to model the interaction between age and Braden Scale scores and subscale scores in PI risk. Of the 6376 ICU patients, 257 (4%) developed a PI (categories 2–4, deep tissue injury, or unstageable) and 516 (8%) developed a hospital-acquired PI of any category. With the exception of the friction and shear subscales, regardless of age, individuals with scores in the intermediate risk levels had the highest likelihood of developing a PI. The relationship between age, Braden Scale subscale scores, and PI development varied among subscales. Maximal preventive efforts should be extended to include individuals with intermediate Braden Scale subscale scores, and age should be considered along with the subscale scores as a factor in care planning.

Introduction

Hospital-acquired pressure injuries (formerly called pressure ulcers) occur among 3% to 24% of patients in the United States and result in longer hospitalization, increased morbidity, and human suffering.[1-3] Among hospitalized older adults, PIs are twice as common among individuals who are admitted to the intensive care unit, which is particularly concerning because older age is a risk factor for both ICU admission and slower healing of PIs.[4,5]

In the United States, PI risk has historically been ascertained using the Braden Scale for Predicting Pressure Injury Risk (Braden Scale) score.[6] The Braden Scale is the sum of six subscales and was developed to be used for planning effective PI prevention interventions; however, the use of summative scores to ascertain PI risk is controversial. A recent systematic review found that formal PI risk-assessment tools with associated intervention protocols were no more effective in preventing PIs than usual care.[7] Therefore, some authors propose that Braden Scale subscale scores, rather than the

cumulative score, should be the focus of PI prevention efforts.[8] Studies detailing PI risk associated with Braden Scale subscale scores among critical-care patients are limited, however.[9] Moreover, although older age is a risk factor for PI development in the critical-care population, no studies have examined PI risk associated with Braden Scale subscale scores in older people specifically.[3,10,11]

The purpose of this study was to identify PI risk associated with the Braden Scale total score and various subscale scores among critical-care patients, and to ascertain whether the risk represented by subscale scores is different between older and younger patients.

Literature Review

The purpose of the Braden Scale is to help clinicians plan effective PI prevention interventions. The scale is comprised of six items, which the authors refer to as subscales: sensory perception, moisture, activity, mobility, nutrition, and friction/shear. Total scores range from 6 (highest risk) to 23 (lowest risk). Prior studies examined the predictive value of the Braden Scale total score among critical-care patients, with mixed results (see Table 5.1). In general, the Braden Scale total score identifies most critical-care patients who go on to develop a PI (high sensitivity), but classifies most critical-care patients as being "at risk" for pressure injuries, and therefore presents low specificity.[9]

Few studies have examined Braden Scale subscale scores among critical-care patients. Cox[9] conducted a systematic review of the literature and concluded that more information was needed. Among studies that examined Braden subscale scores, four subscales (friction and shear, moisture, mobility, and sensory perception) demonstrated some predictive value on multivariate analysis, whereas two (nutrition and activity) did

Table 5.1

Braden Scale Predictive Validity

Study	Sample	Design	Pressure Injury Incidence and Categories	Findings
Jiricka et al.[12]	85 intensive care unit (ICU) patients in the United States	Prospective	56% (categories 1-4)	Braden Scale at cutoff point 11: Sensitivity 75% Specificity 64% Positive predictive value 73.5% Negative predictive value 66.7%
Lee et al.[15]	112 ICU patients in Korea	Prospective	31.3% (categories 1-4)	Braden Scale: Sensitivity 97% Specificity 26% Positive predictive value 37% Negative predictive value 95%
Pender & Frazier[16]	40 mechanically ventilated ICU patients in the United States	Prospective record review	20% (categories 1-4)	No relationship identified between Braden score and pressure injury (PI) development
Feuchtinger et al.[17]	53 surgical ICU patients in Germany	Prospective	49% (categories 1-4; all but one injury were category 1)	Braden Scale at cutoff point 11: Sensitivity 31% Specificity 100% Positive predictive value 100% Negative predictive value 41%
Fernandes & Caliri[18]	48 ICU patients in Brazil	Prospective	48% (categories 1-4)	Bivariate results showed individuals who developed PIs had lower Braden Scale scores (p = 0.0–01) No multivariate results reported
Kim et al.[19]	219 surgical ICU	Prospective	18.3% (categories	Braden Scale at cutoff point 14:

Table 5.1 (Continued)

Study	Sample	Design	Pressure Injury Incidence and Categories	Findings
Kim et al.[19] (continued)	patients in Korea		1-4)	Sensitivity 92.5% Specificity 69.8% Positive predictive value 40.6%
Kim et al.[19] (continued)				Negative predictive value 97.6%
Kaitani et al.[20]	98 ICU/high-care unit patients in Japan	Prospective	11.2% (categories 1-4)	Individuals in the "moderate risk" Braden score group (13-14) had greater PI incidence than those in the "high risk" group (<12)
Cho & Noh[21]	715 ICU patients in Korea	Retrospective	5.9% (categories 1-4)	Note: The Braden Scale was administered to only 11% of ICU patients, for reasons that are unclear. Braden Scale at cutoff point 13: Sensitivity 75.9% Specificity 47.3% Positive predictive value 18.1% Negative predictive value 92.8%
Slowikowski & Funk[3]	369 ICU patients in the United States	Prospective	23.9% (categories not reported)	The Braden Scale was significant on multivariate logistic regression; odds ratio 1.3
Iranmanesh et al.[22]	82 trauma ICU patients in Iran	Prospective	13.4% (categories not reported)	Bivariate results showed that individuals who developed PI had lower Braden Scale scores (p <0.05) No multivariate results reported
Cox[10]	347 medical–surgical ICU patients in the United States	Retrospective	18.7% (categories 1-4, DTI, and unstageable)	Braden Scale at cutoff point 18: Sensitivity 100% Specificity 7% Positive predictive value 20% Negative predictive value 100%

Table 5.1 (Continued)

Study	Sample	Design	Pressure Injury Incidence and Categories	Findings
Tschannen et al.[23]	3,225 surgical ICU and intermediate-care patients in the United States	Retrospective	12% (categories 1-4, DTI, and unstageable)	The admission Braden Scale was significant upon multivariate logistic regression analysis; odds ratio 0.89

Note. DTI = deep tissue injury.

not.[9,10,12–14] However, a major methodological limitation noted by Cox10 was the lack of a repeated-measures approach; the subscale scores were taken from a single point in time (eg, admission) or were averaged in some way, which failed to capture the dynamic nature of critical-care patients' physiologic status.

In an effort to analyze the risk represented by the various Braden subscales, Gadd[8] conducted a case study that included chart reviews of 20 patients with hospital-acquired PIs and concluded that some injuries might have been avoided if preventive interventions based on Braden Scale subscale scores were implemented. Information is still needed pertaining to the risk represented by the various subscale scores, however.

Methods

Design

Working with a biomedical informatics team, we queried an enterprise data warehouse for electronic health record (EHR) data matching our sampling criteria and variables of interest. We refined the query and the data using an iterative approach entailing data-validation procedures and iterative review by domain experts, data stewards, and the biomedical informatics team. We validated the data extracted from the EHR by manually comparing the values and date/time stamps found in the extracted data to those displayed in the human-readable system views for 60 cases. On implementing the fully developed query for all manually validated cases, we found consistent values and date/time stamps.

Sample

The sample consisted of patients admitted to the ICU at an academic medical center and Level 1 trauma center between January 1, 2008 and May 1, 2013 who met inclusion criteria, which were admission to the adult surgical ICU or cardiovascular ICU, either directly or following an acute-care stay. We included individuals younger than age 18 years who were admitted to the adult ICU in an effort to study the Braden Scale as it was actually used among all patients in the adult surgical ICUs; however, we excluded patients with PIs present on admission to the ICU due to concern about misattribution of community-acquired PIs as hospital-acquired PIs.

Measures

During the time period encompassed by the study, it was standard practice for nurses in the ICU to conduct a head-to-toe skin assessment and record Braden Scale scores at least once during each 12-hr shift (twice per day). The nurses received annual training on the Braden Scale and also on PI identification. We averaged the Braden Scale score for each shift to derive a once-daily value. The primary outcome variable was a hospital-acquired category 2–4 PI, deep tissue injury (DTI), or unstageable injury. The secondary outcome variable was a hospital-acquired pressure injury (HAPI) of any category (1–4, DTI, or unstageable). We did not include category 1 PIs in the primary analysis due to concern about the difficulty in differentiating between transient redness caused by friction or dermatitis versus true tissue injury[24]; however, we did include category 1 injuries in a separate secondary analysis in an effort to capture the full spectrum of tissue injury.

Analysis

We used time-dependent survival analysis to determine the hazards of developing a PI based on the total Braden Scale and each Braden subscale. We chose time-varying Cox regression to take into account all of the Braden Scale measurements, assuming that the hazard of developing a PI changes in synchrony with the Braden Scale changes. For each subscale and for the total Braden Scale score, the lowest risk category represented the reference. In addition, we used time-dependent Cox regression with natural cubic splines to model the association of developing a PI with age, by the total Braden Scale score and also by each Braden subscale category. We performed the analysis using statistical software STATA 13 and the statistical significance level was defined at alpha = 0.05.

Results

Sample

The query produced 7218 records. We omitted 841 records due to incomplete patient identification (ID) (examples include a date instead of an ID or single-digit numbers). The final sample therefore consisted of 6376 patients admitted to the adult surgical ICU or adult cardiothoracic ICU. The mean age was 54 +/- 19 years. There were 2403 females (38%) and 3924 males (62%). The majority of the sample was White (*n* = 4838; 78%). The mean length of stay was 10 days and ranged from 1 to 229 days.

Pressure Injury

Two hundred and fifty seven individuals (4%) developed PIs of category 2 or greater and 516 (8%) developed PIs of category 1 or greater (see Table 5.2).

Table 5.2

Pressure Injury Categories

Category	Category 1 or Above	Category 2 or Above
Category 1	259 (50%)	N/A
Category 2	214 (41.5%)	214 (83%)
Category 3	13 (2.5%)	13 (5%)
Category 4	4 (0.8%)	4 (1.5%)
Deep tissue injury	8 (1.5%)	8 (3.1%)
Unstageable	18 (3.5%)	18 (7%)

Demographic information for individuals with and without PIs is presented in Table 5.3.

Risk for Pressure Injury: Categories 2–4, Deep Tissue Injury, and Unstageable Injury

Individuals with a cumulative Braden Scale score between 10 and 12 (high risk) were 8.4 times (95% confidence interval [CI] 5.7–12.6) more likely to develop a PI compared with people whose Braden Scale score indicated no risk (≥19). Among those in the severe-risk category (total score ≤9), the chances of developing a PI were similar to patients in the moderate cumulative Braden score category (13–14), with hazard rate ratios of 5.3 (95% CI 1.6–17.1) and 5.7 (95% CI 3.9–8.3), respectively (see Table 5.4).

The finding that individuals at a cumulative “high risk” score were more likely to develop a PI than individuals at the “severe risk” level is also reflected in the results for the various subscale scores, with the exception of the friction/shear subscale, according to which people with the most severe score were most likely to develop PIs (Table 5.4). The effect was particularly pronounced in the moisture and mobility subscales. People in the

Table 5.3

Demographics

Variable	Total Population	Category 1 or Above		Category 2 or Above	
		Intact Skin	PI	Intact Skin	PI
Age [mean (*SD*, minimum–maximum, years]	54 (19), 12–100	53 (19), 12–100	59 (17), 14–96	53 (19), 12–100	59 (16), 19–96
No. available (No. missing)	6317(60)	5842(19)	475(41)	6061(59)	256(1)
Gender					
Male [*n* (%)]	3,924 (62%)	3,626 (62%)	293 (62%)	3,723 (62%)	201 (63%)
Female [*n* (%)]	2,403 (38%)	2,216 (38%)	182 (38%)	2,286 (38%)	117 (37%)
No. available (No. missing)	6317 (60)	5842 (19)	475 (41)	6061 (59)	256 (1)
Race					
White [*n* (%)]	4,838 (78%)	4,455 (77%)	375 (80%)	4,601 (78%)	237 (76%)
Non-White [*n* (%)]	1,395 (22%)	1,300 (23%)	94 (20%)	1,320 (22%)	75 (24%)
No. available (No. missing)	6224(153)	5755(106)	469(47)	5972(148)	256(1)
Length of stay[a] [mean (std), days]	10 (12), 1–229	9 (9), 1–224	27 (24), 1–229	9 (9), 1–224	30 (27), 1–229
No. available (No. missing)	6317(60)	5842(19)	469(47)	6061(59)	256(1)

Note. PI = pressure injury/-ies; No. = number of cases.
[a] Partial days are included as a day if >12 hr.

"often moist" category were 12.5 times (95% CI 7.8–20.2) as likely as those who were in the "rarely moist" category to develop a PI, while the risk of developing a PI was relatively lower in the more severe "constantly moist" category (hazard rate ratio [HRR] = 6.8, 95% CI 2.2–21.5). Similarly, individuals with "very limited" mobility were 7.7 times as likely (95% CI 4.9–12.1) to develop a PI compared to patients without mobility limitations, whereas those who were deemed "completely immobile" were only 4.9 times as likely (95% CI 2.7–8.8) to develop a PI compared to individuals without mobility limitations.

Table 5.4

Hazards of Developing a Category 2–4, Deep Tissue Injury, or Unstageable Pressure Injury

Braden Scale/Subscale Category	Hazard Rate Ratio (95% CI), *p* Value		
	Total ICU Population	Age > 65 Years	Age ≤ 65 Years
Total Braden Scale (ref = no risk, total score ≥ 19)			
Mild risk (total score 15–18)	2.2 (1.6, 3.2), $p<0.001$	1.7 (1.0, 2.8), $p = 0.053$	2.4 (1.5, 3.7), $p<0.001$
Moderate risk (total score 13–14)	5.7 (3.9, 8.3), $p<0.001$	4.1 (2.4, 7.2), $p<0.001$	6.1 (3.9, 9.8), $p<0.001$
High risk (total score 10–12)	8.4 (5.7, 12.6), $p<0.001$	4.1 (2.1, 8.3), $p<0.001$	10.4 (6.5, 16.6), $p<0.001$
Severe risk (total score ≤9)	5.3 (1.6, 17.1), $p = 0.005$	(Too few cases)	2.1 (0.3, 15.1), $p = 0.480$
Sensory Perception (ref = no impairment, score = 4)			
Slightly limited (score = 3)	2.1 (1.6, 2.7), $p<0.001$	2.9 (1.4, 3.0), $p<0.001$	2.1 (1.5, 2.8), $p<0.001$
Very limited (score = 2)	2.0 (1.4, 2.8), $p<0.001$	1.3 (0.7, 2.6), $p = 0.400$	2.3 (1.6, 3.5), $p<0.001$
Completely limited (score = 1)	1.1 (0.6, 2.1), $p = 0.738$	0.8 (0.2, 3.1), $p = 0.713$	1.3 (0.6, 2.7), $p = 0.487$
Moisture (ref = rarely moist, score = 4)			
Occasionally moist (score = 3)	5.7 (4.5, 7.1), $p<0.001$	5.8 (3.9, 8.5), $p<0.001$	5.7 (4.3, 7.6), $p<0.001$
Often moist (score = 2)	12.5 (7.8, 20.2), $p<0.001$	45.5 (20.7, 100.3), $p<0.001$	8.7 (4.6, 16.2), $p<0.001$
Constantly moist (score = 1)	6.8 (2.2, 21.5), $p = 0.001$	13.7 (1.9, 98.8), $p = 0.010$	5.8 (1.4, 23.5), $p = 0.014$
Activity (ref = walks frequently, score = 4)			
Walks occasionally (score = 3)	3.1 (1.7, 5.9), $p<0.001$	7.5 (1.8, 31.2), $p = 0.005$	2.0 (1.0, 4.2), $p = 0.060$
Chairfast (score = 2)	4.3 (2.3, 8.1), $p<0.001$	5.7 (1.3, 24.3), $p = 0.019$	4.1 (2.0, 8.2), $p<0.001$
Bedfast (score = 1)	3.3 (1.8, 6.0), $p<0.001$	5.6 (1.4, 22.9), $p = 0.017$	2.7 (1.4, 5.4), $p = 0.004$
Mobility (ref – no limitations, score = 4)			
Slightly limited (score = 3)	3.8 (2.4, 6.0), $p<0.001$	4.0 (1.8, 8.8), $p = 0.001$	3.6 (2.1, 6.3), $p<0.001$
Very limited (score = 2)	7.7 (4.9, 12.1), $p<0.001$	7.2 (3.2, 15.9), $p<0.001$	7.9 (4.5, 13.6), $p<0.001$
Completely immobile (score = 1)	4.9 (2.7, 8.8), $p<0.001$	1.7 (0.4, 8.1), $p = 0.511$	6.1 (3.1, 12.1), $p<0.001$

Table 5.4 (Continued)

Braden Scale/Subscale Category	Hazard Rate Ratio (95% CI), *p* Value		
	Total ICU Population	Age > 65 Years	Age ≤ 65 Years
Nutrition (ref = excellent, score = 4)			
Adequate (score = 3)	4.0 (1.7, 9.8), *p* = 0.002	3.8 (0.9, 15.7), *p* = 0.060	4.2 (1.3, 13.1), *p* – 0.015
Probably inadequate (score = 2)	4.4 (1.8, 10.8), *p* = 0.001	3.8 (0.9, 15.9), *p* = 0.065	4.8 (1.5, 15.2), *p* = 0.008
Very poor (score = 1)	4.0 (1.1, 15.0), *p* = 0.038	3.0 (0.3, 33.5), *p* = 0.365	4.7 (0.9, 23.1), *p* = 0.060
Friction and Shear (ref = no apparent problem, score = 3)			
Potential problem (score = 2)	5.2 (4.0, 6.7), *p*<0.001	3.5 (2.3, 5.4), *p*<0.001	6.2 (4.5, 8.6), *p*<0.001
Problem (score = 1)	454.6 (30.8, 67.4), *p*<0.001	31.7 (16.4, 61.4), *p*<0.001	55.0 (33.7, 89.6), *p*<0.001

Note. CI = confidence interval; ICU = intensive care unit; ref = reference.

Risk of Pressure Injury: All Categories

Results for the inclusion of category 1 PIs in the PI outcome variable were similar to the results for categories 2–4, DTI, and unstageable injuries described above (see Table 5.5). Individuals with a cumulative Braden Scale score between 10 and 12 (high risk) were 6.7 times (95% CI 4.8–9.4) more likely to develop a PI compared with people whose Braden Scale score indicated no risk (≥19). Among those in the severe risk category (total score ≤9), the chances of developing a PI were similar to patients in the moderate cumulative Braden score category (13–14), with hazard rate ratios of 4.6 (95% CI 1.7–12.7) and 4.8 (95% CI 3.6–6.6), respectively (Table 5.4).

The finding that individuals with a cumulative high-risk score were more likely to experience PI development than individuals at the severe-risk level is also reflected in the results for the various subscale scores, with the exception of the friction/shear subscale, according to which individuals with the most severe score were most likely to develop PIs (Table 5.5). The effect was particularly pronounced in the moisture, activity, and mobility subscales. People in the "often moist" category were 8.8 times (95% CI 5.7–13.6) as likely as those who were in the "rarely moist" category to develop a PI, while the risk of developing a PI was relatively lower in the more severe "constantly moist" category (HRR = 4.2, 95% CI 1.4–13.2). People whose activity fell in the midrange severity level of "chairfast" were 7.2 times (95% CI 4.0–13.0) more likely to develop a PI, whereas those who were bedfast were at relatively lower risk, with an HRR of 4.5 (95% CI 2.5–8.0). Similarly, individuals with "very limited" mobility were 5.7 times as likely (95% CI 4.0–8.0) to develop a PI compared to patients without mobility limitations, whereas those who were deemed "completely immobile" were 4.2 times as

Table 5.5

Hazards of Developing a Category 1–4, Deep Tissue Injury, or Unstageable Pressure Injury

Braden Scale/Subscale Category	Hazard Rate Ratio (95% CI), *p* Value		
	Total ICU Population	Age >65 Years	Age ≤65 Years
Total Braden Scale (ref = no risk, total score ≥19)			
Mild risk (total score 15–18)	2.6 (2.0, 3.4), *p*<0.001	2.2 (1.4, 3.4), *p*<0.001	2.8 (2.0, 4.1), *p*<0.001
Moderate risk (total score 13–14)	4.8 (3.6, 6.6), *p*<0.001	4.1 (2.5, 6.6), *p*<0.001	5.3 (3.6, 7.9), *p*<0.001
High risk (total score 10–12)	6.7 (4.8, 9.4), *p*<0.001	4.1 (2.2, 7.4), *p*<0.001	8.4 (5.6, 12.7), *p*<0.001
Severe risk (total score ≤19)	4.6 (1.7, 12.7), *p* = 0.003	(Too few cases)	2.8 (0.7, 11.7), *p* = 0.151
Sensory Perception (ref = no impairment, score = 4)			
Slightly limited (score = 3)	1.7 (1.4, 2.1), *p*<0.001	1.5 (1.1, 2.1), *p* = 0.014	1.9 (1.5, 2.4), *p*<0.001
Very limited (score = 2)	1.7 (1.3, 2.3), *p*<0.001	1.0 (0.5, 1.7), *p* = 0.866	2.2 (1.6, 3.1), *p*<0.001
Completely limited (score = 1)	1.1 (0.7, 1.8), *p* = 0.736	1.1 (0.4, 2.6), *p* = 0.883	1.1 (0.6, 2.1), *p* = 0.656
Moisture (ref = rarely moist, score = 4)			
Occasionally moist (score = 3)	5.0 (4.1, 6.0), *p*<0.001	4.5 (3.3, 6.2), *p*<0.001	5.3 (4.2, 6.6), *p*<0.001
Often moist (score = 2)	8.8 (5.7, 13.6), *p*<0.001	26.3 (12.8, 54.2), *p*<0.001	6.5 (3.7, 11.5), *p*<0.001
Constantly moist (score = 1)	4,2 (1.4, 13.2), *p* = 0.013	7.6 (1.1, 54.7), *p* = 0.043	3.8 (0.9, 15.2), *p* = 0.063
Activity (ref = walks frequently, score = 4)			
Walks occasionally (score = 3)	4.6 (2.5, 8.3), *p*<0.001	7.9 (2.5, 25.3), *p*<0.001	3.3 (1.6, 6.7), *p* = 0.001
Chairfast (score = 2)	7.2 (4.0, 13.0), *p*<0.001	8.0 (2.5, 25.9), *p* = 0.001	6.9 (3.5, 13.8), *p*<0.001
Bedfast (score = 1)	4.5 (2.5, 8.0), *p*<0.001	5.6 (1.8, 17.6), *p* = 0.004	4.1 (2.1, 7.9), *p*<0.001
Mobility (ref = no limitations, score = 4)			
Slightly limited (score = 3)	3.5 (2.5, 5.0), *p*<0.001	3.3 (1.9, 5.8), *p*<0.001	3.6 (2.3, 5.5), *p*<0.001
Very limited (score = 2)	5.7 (4.0, 8.0), *p*<0.001	4.7 (2.6, 8.4), *p*<0.001	6.1 (4.0, 9.5), *p*<0.001
Completely immobile (score = 1)	4.2 (2.6, 6.7), *p*<0.001	3.3 (1.4, 7.9), *p* = 0.007	4.7 (2.7, 8.2), *p*<0.001
Nutrition (ref = excellent, score = 4)			
Adequate (score = 3)	3.1 (1.6, 5.8), *p*<0.001	1.9 (0.8, 4.3), *p* = 0.124	4.8 (1.8, 13.0), *p* = 0.002

Table 5.5 (Continued)

Braden Scale/Subscale Category	Hazard Rate Ratio (95% CI), *p* Value		
	Total ICU Population	Age >65 Years	Age ≤65 Years
Nutrition (continued)			
Probably inadequate (score = 2)	3.4 (1.8, 6.5), *p*<0.001	2.1 (0.9, 5.0), *p* = 0.074	5.3 (2.0, 14.5), *p* < 0.001
Very poor (score = 1)	3.0 (1.1, 8.4), *p* = 0.031	1.9 (0.4, 9.6), *p* = 0.419	4.8 (1.2, 19.2), *p* = 0.027
Friction and Shear (ref = no apparent problem, score = 3)			
Potential problem (score = 2)	4.7 (3.8, 5.7), *p*<0.001	4.1 (2.9, 5.7), *p*<0.001	4.9 (3.8, 6.3), *p*<0.001
Problem (score = 1)	27.6 (19.1, 39.7), *p*<0.001	22.5 (12.2, 41.5), *p*<0.001	30.3 (19.2, 47.6), *p*<0..001

Note. CI = confidence interval; ICU – intensive care unit; ref = reference.

likely (95% CI 2.6–6.7) to develop a PI compared to individuals without mobility limitations.

Age and Braden Scale Score

Tables 5.4 and 5.5 identify the hazards of developing a PI of category 2 and greater and category 1 and greater, respectively, associated with the Braden Scale categories for the total population and also for individuals who are older or younger than 65 years. However, the relationship between the Braden Scale subscale score and age was not linear in some subscales, and therefore, in an effort to fully represent the age dimension, we used time-dependent Cox regression with natural cubic splines to model the association of developing a category 2 or greater PI with age.

Our data show that individuals in the high- and severe-risk cumulative Braden Scale categories experienced increases in risk for PI development with advancing age, whereas the effect of age within the moderate and mild risk categories was relatively static (see Figure 5.1). The relationship between the sensory perception subscale, age, and PI risk was linear, with increased risk at younger ages, and the increased risk among younger people was particularly pronounced in the “very limited” sensory perception group (Figure 5.2). Moisture was associated with increased risk for PI among older individuals who were often moist, as opposed to older individuals in the occasionally or constantly moist categories, while younger people who were often moist did not experience increased risk relative to those who were either occasionally or constantly moist (Figure 5.3).

Pressure injury risk associated with activity was also more pronounced among older people, particularly among those who were in the “walks occasionally” category

Figure 5.1 Total Braden Scale.

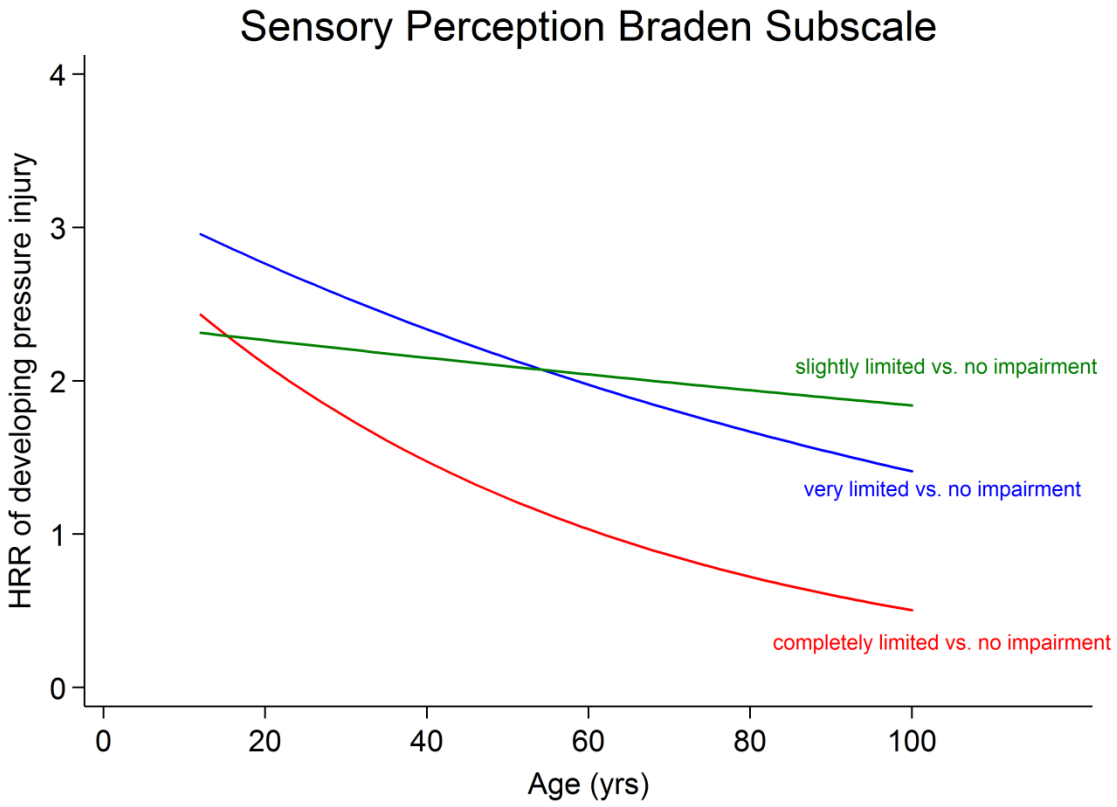

Figure 5.2 Sensory perception Braden subscale.

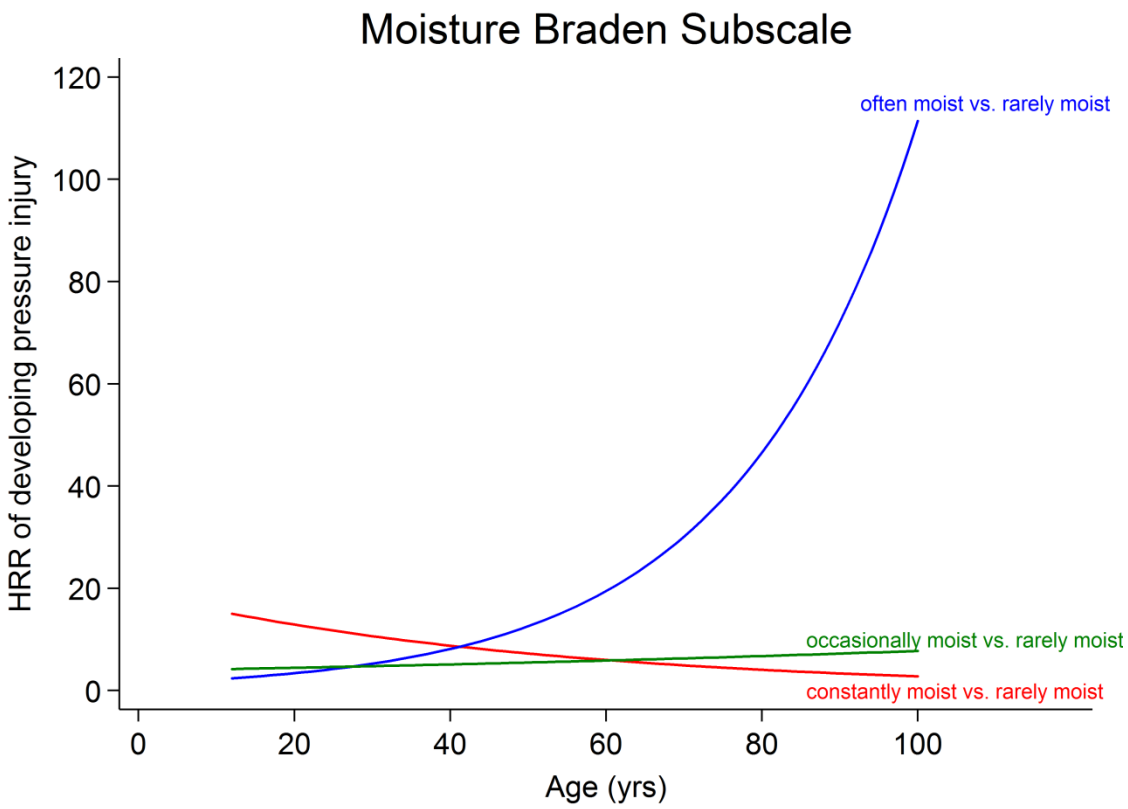

Figure 5.3 Moisture Braden subscale.

(Figure 5.4), whereas altered mobility (very limited mobility or completely immobile) conferred the most risk among younger people (Figure 5.5). The nutrition subscale showed increased rates of PI development among older people, but not younger people, who had "very poor" nutrition status (Figure 5.6). Finally, a friction and shear score of "problem" was associated with dramatically increased risk for PI compared to a score of "potential problem" or "no apparent problem" at all ages (Figure 5.7).

Discussion

A major strength of this study was the use of a large data set incorporating repeated measures of Braden Scale scores that therefore reflects the variability in an individual's risk status throughout his or her ICU stay. Although other studies have examined Braden subscale scores, those studies that relied on a single assessment (eg, admission Braden score), a mean measure, or cross-sectional approaches did not take into consideration the dynamic nature of a patient's physiologic status in the ICU.[9]

The finding that, with the exception of the friction/shear subscale, individuals with scores in the intermediate risk levels had the highest likelihood of developing a PI, was unexpected. We speculate that nurses noted the patients at most severe risk and applied maximal preventive measures, which effectively prevented some PIs from occurring among individuals in the highest risk categories, whereas patients with moderate risk scores may not have received the same level of vigilance as those with the highest risk scores. The lack of information about preventive measures, however, is an important limitation. Although we speculate that high-risk Braden subscale scores cued the nurses and healthcare team to apply maximal preventive interventions for high-risk patients, it is also possible that another, unrecorded factor contributes to higher risk of PI

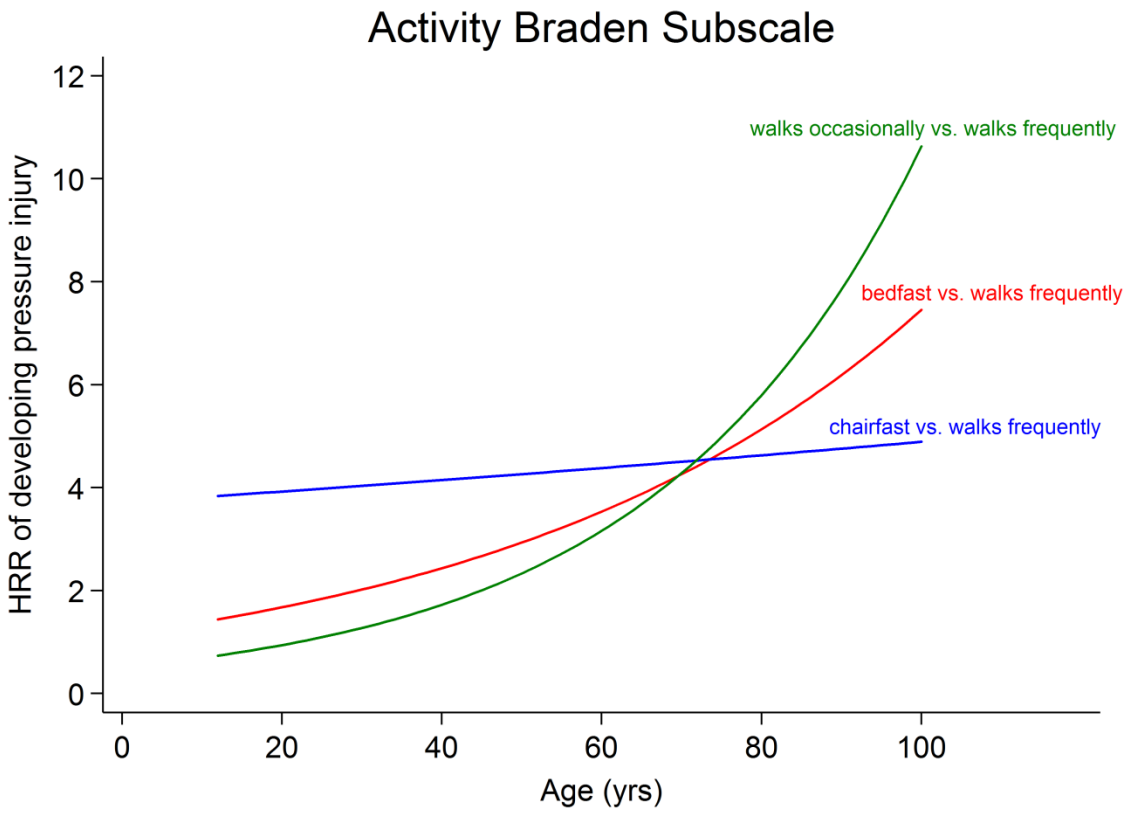

Figure 5.4 Activity Braden subscale.

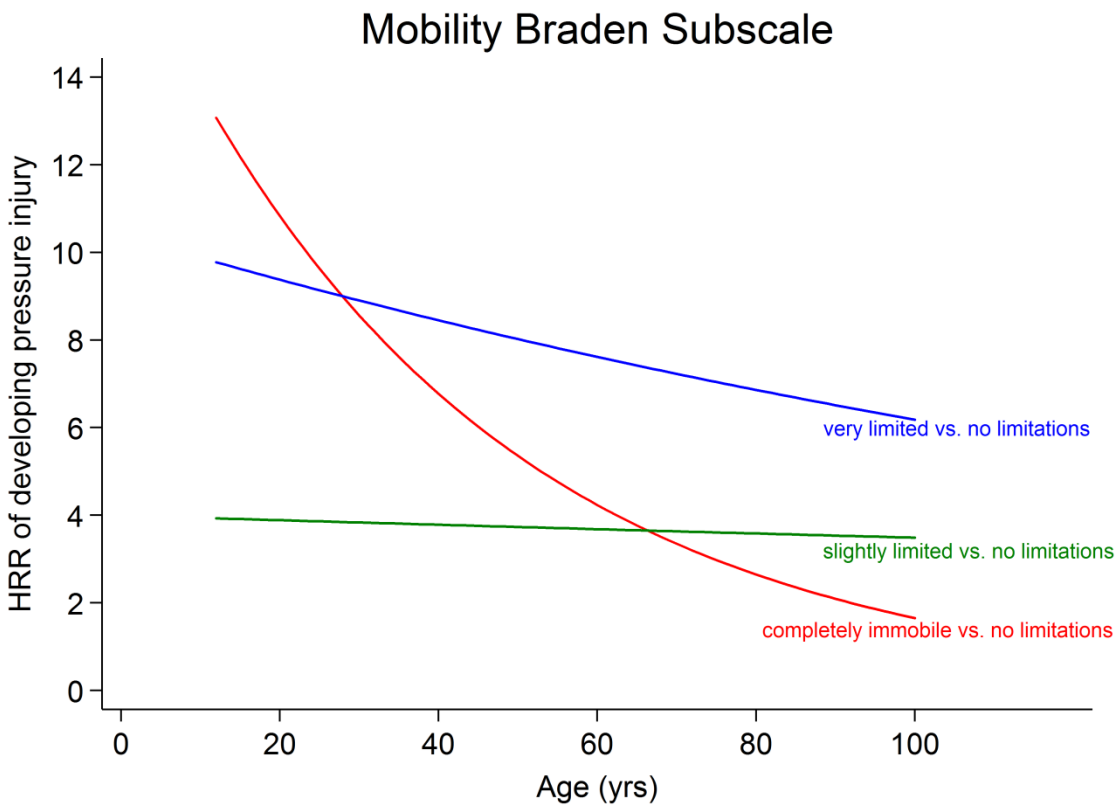

Figure 5.5 Mobility Braden subscale.

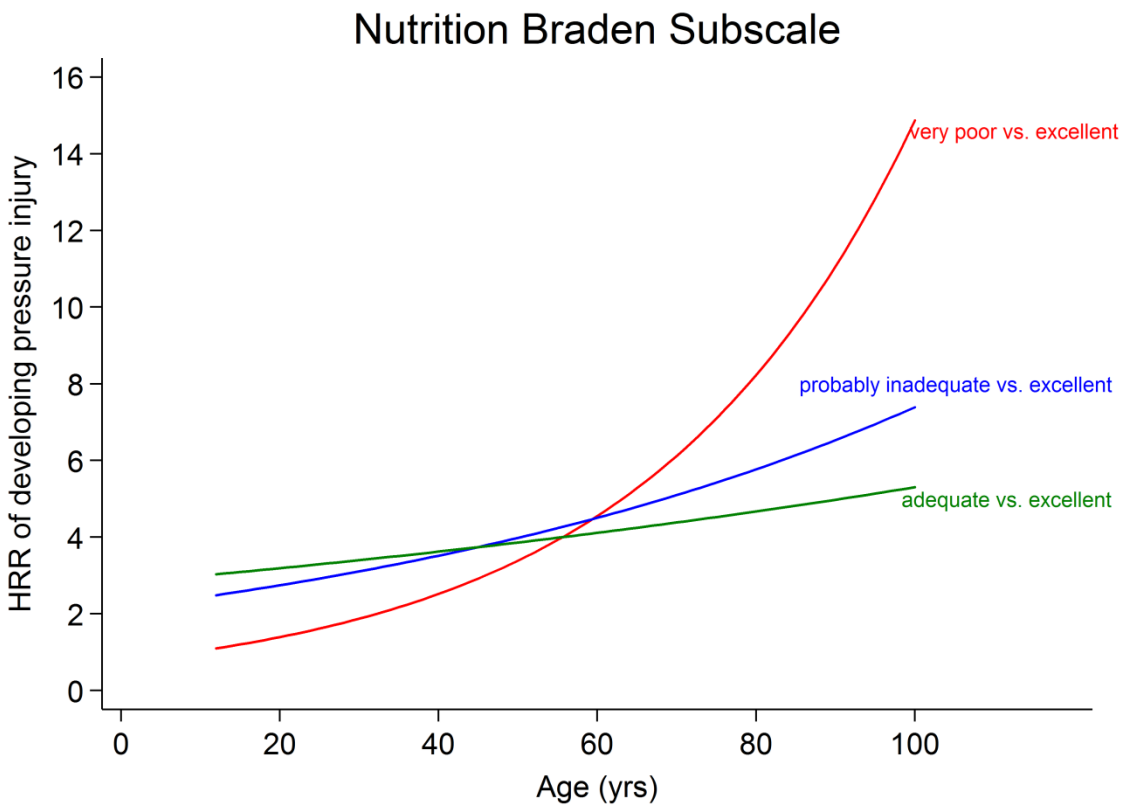

Figure 5.6 Nutrition Braden subscale.

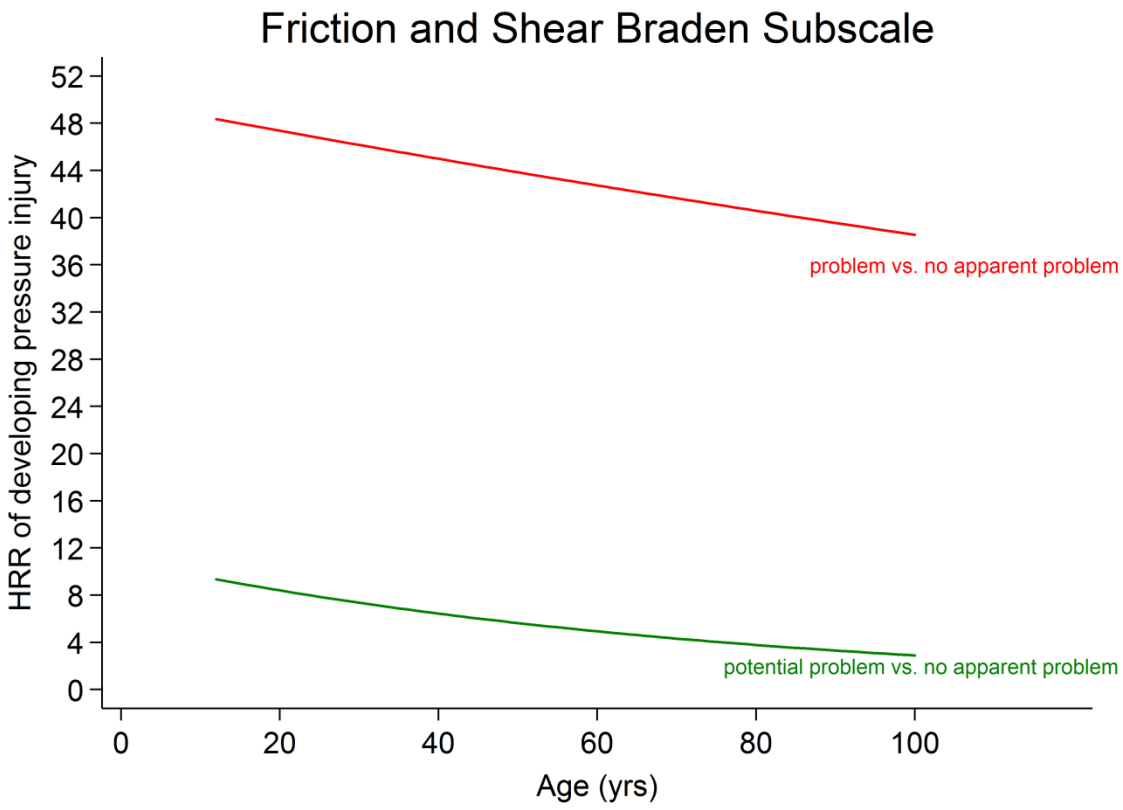

Figure 5.7 Friction and shear Braden subscale.

development among midrange patients.

The interaction between age and Braden Scale scores and subscale scores, particularly the activity, moisture, sensory perception, and nutrition subscales, added an important dimension that should be considered as a factor in care planning. Older people with midrange-severity activity scores ("walks occasionally") were at markedly increased risk for PI development compared with younger people with the same score (Figure 5.4). The results suggest that nurses should implement maximal preventive measures for older people with even mildly limited activity ("walks occasionally" vs. "walks frequently").

Moisture was associated with increased risk for PI among older people who were often moist, as opposed to older people in the occasionally or constantly moist categories, while younger people who were often moist did not experience increased risk relative to those who were either occasionally or constantly moist (Figure 5.3). It is likely that even moderate or episodic occasions of moisture are particularly harmful to older people's skin due to age-related changes in tissue resilience[25]; therefore, clinicians caring for older people in the ICU should be especially diligent in moisture management.

Interestingly, the sensory perception subscale showed increased risk for PI development among *younger* critical-care patients (Figure 5.2). Sensory perception is operationalized in the Braden Scale based on an individual's responsiveness and ability to feel pain or discomfort, and has been implicated as an important factor for PI development among trauma and orthopedic patients.[26] Although exact numbers are not available, trauma patients make up a larger proportion of younger patients as opposed to older patients at our study site, a Level 1 trauma center. Trauma patients are more likely than others to present with conditions that alter sensory perception, such as head or spinal

cord injuries. It is possible, therefore, that the increased risk associated with altered sensory perception among younger people is associated with the effects of traumatic injury in that age group.

Older people with "very poor" nutrition had higher rates of PI development, whereas younger people with equal nutrition were not at increased risk (Figure 5.6). Although prior studies conducted among critical-care patients did not reveal an association between PI development and nutrition status, it is possible that age moderates the relationship due to decreased physiologic reserves among older people.[3,10,20]

Unlike the cumulative score and the other subscales, results for the friction and shear subscale showed markedly increased risk among individuals of all ages, with the most severe subscale rating ("problem"). Developments in PI research indicate that friction-induced skin injuries are not true PIs, whereas shearing forces cause a decrease in regional blood flow and therefore are important in PI etiology.[27,28] Prior studies documented the harmful effects of shear among critical-care patients. Cox[10] noted that critical-care patients with a friction and shear score of "problem" were more than five times (95% CI 1.423–22.95) as likely to develop PIs compared to the rest of her sample. Thus, measures to prevent or ameliorate shearing forces, including lifts, should be prioritized for all critical-care patients at risk for shear.[29]

Conclusion

Our findings show that individuals with Braden Scale scores and subscale scores in the intermediate risk levels had the highest likelihood of developing a PI among all subscale categories except the friction and shear subscale, according to which patients with the most severe score were at markedly increased risk for PI development. We

speculate that high-risk Braden subscale scores cued the nurses and healthcare team to apply maximal preventive interventions for the patients at highest risk, and propose that in light of our results, maximal preventive interventions should be extended to patients with midrange risk scores. We also found that the risk associated with the subscales varied with age, indicating that age should be considered along with the subscale scores as a factor in care planning. In future studies, researchers should seek to quantify the effects of treatment measures related to Braden Scale scores and subscale scores.

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CHAPTER 6

PREDICTING PRESSURE INJURY RISK AMONG CRITICAL-CARE PATIENTS: A MACHINE LEARNING APPROACH

Introduction

Hospital-acquired pressure injuries (HAPIs) occur among 3%–24% of critical-care patients in the United States and result in longer hospitalization, increased morbidity, and human suffering (Frankel, Sperry, & Kaplan, 2007; Graves, Birrell, & Whitby, 2005; Slowikowski & Funk, 2010). Although HAPIs are common, some pressure injuries (PIs) can be prevented using measures that are not feasible for every patient because of cost (Jackson et al., 2011). In addition, recognizing people at highest risk for a HAPI is important because clinicians are then able to conduct thorough skin assessments in an effort to identify PIs at the earliest, reversible stage (Halfens, Bours, & Van Ast, 2001). Therefore, recommended standards of practice include assessing patients for PI risk at admission and with any change in clinical status (National Pressure Ulcer Advisory Panel [NPUAP], European Pressure Ulcer Advisory Panel, & Pan Pacific Pressure Injury Alliance, 2014). Unfortunately, identification of high-risk individuals in the intensive care unit (ICU) is problematic because currently available risk-assessment tools have high sensitivity but low specificity in the critical-care population and tend to classify most patients as being at “high risk” (Cox, 2012). Clearly, a predictive model with

adequate sensitivity and (especially) specificity is needed so that clinicians can differentiate between critical-care patients to identify those at highest risk for PI.

Raju, Su, Patrician, Loan, and McCarthy (2015) advocated for a machine learning approach to build a useful PI predictive model because machine learning techniques can effectively and efficiently utilize large amounts of clinical data that are routinely collected in electronic health records (EHRs). Machine learning is a type of artificial intelligence that can be applied to building predictive models but is rarely used in PI research (Raju et al., 2015). The authors specifically recommended a type of machine learning called the *random forest approach*, a method that uses an ensemble decision tree, where random subsets are drawn from the data with replacement (Raju et al., 2015). The advantages of an RF approach are that (a) all of the data can be used for training and validation while avoiding the decision-tree tendency to overfit the model, and (b) the approach is relatively robust in the face of multicollinearity and missing data (Garge, Bobashev, & Eggleston, 2013; Guidi, Pettenati, Miniati, & Iadanza, 2013). Therefore, the purpose of our study was to develop a model to predict PI development among critical-care patients via a machine learning/RF approach.

Literature Review

Pressure Injury

Pressure injuries, formerly called pressure ulcers, are localized areas of injury to skin and/or underlying tissue that occurs as a result of pressure or pressure in combination with shear (NPUAP, 2016). There are six categories of PIs defined by NPUAP. Category 1 PIs are areas of nonblanching redness or discoloration in intact skin. Category 2 PIs represent partial-thickness tissue loss with exposed, viable dermis.

Category 3 PIs are full-thickness wounds that do not extend into muscle, bone, or tendon. Category 4 PIs are full-thickness wounds that extend down to muscle, tendon, or bone. Deep-tissue injuries (DTIs) are areas of intact or nonintact skin with a localized area of persistent, nonblanchable, deep-red, maroon, or purple discoloration revealing a dark wound bed or blood-filled blister. Finally, unstageable PIs are areas of full-thickness tissue loss that cannot be evaluated because the area is obscured by eschar or slough.

The NPUAP, European Pressure Ulcer Advisory Panel (EPUAP), and Pan Pacific Pressure Injury Alliance (PPPIA; 2014) contend that PIs are caused by a combination of mechanical boundary conditions and the susceptibility and tolerance of the individual. Mechanical boundary conditions refer to magnitude and duration of the mechanical load and the type of mechanical loading (pressure, shear, or friction). Susceptibility and tolerance of the individual encompass factors that reduce an individual's ability to withstand the mechanical load, such as age-related changes in tissue morphology, infection, altered nutrition, or poor perfusion.

Random Forest

The RF algorithm derives from the classification tree, where a training set of data is successively split into partitions, or nodes, so that ultimately a previously unseen record can be accurately assigned to a class (in this case, development of a HAPI or no HAPI; Izmirlian, 2004). Advantages of decision trees include ease of use and interpretation, resistance to outliers, the ability to work efficiently with a large number of predictor variables, and built-in mechanisms for handing missing data by using correlated variables (Izmirlian, 2004; Raju et al., 2015). The decision-tree approach uses the best-fitting variable at each node, and therefore the resulting model fits nearly perfectly—

which is problematic, because the model is overfitted (Raju et al., 2015).

The RF approach retains the advantages of a classification tree but addresses the problem of overfit via bootstrap aggregation, also known as bagging (Izmirlian, 2004). Bagging refers to the collection of many random subsamples of data with replacement, so that for each sample (bootstrap) taken there will be samples left behind that were not included. A new decision tree is trained on each sample. Instead of using the best-fitting variable in the data set at each node, a number equal to the square root of the number of features are selected at random and the node is spilt using the best fit out of that group (Liaw & Wiener, 2002). The RF approach generates many individual decision trees, and ultimately each tree gets one vote for the class (in this case, "yes" or "no" for PI). Although RF does not provide an effect size for each variable, as in hypothesis-based research, output does include variable importance in rank order. Note that variable importance may be due to complex interactions with other variables rather than a direct causal relationship (Liaw & Wiener, 2002).

Methods

Data Preprocessing

A biomedical informatics team assisted us in our data discovery process. We queried an enterprise data warehouse for EHR data consistent with our sampling criteria and variables of interest. We used an iterative approach to refine our query via validation procedures and review by domain experts, data stewards, and the biomedical informatics team. We validated the data extracted from the EHR by manually comparing the values and date/time stamps found in the extracted data to those displayed in the human-readable system views for 30 cases. On implementing the fully developed query for all

manually validated cases, we found consistent values and date/time stamps. Individual variables were cleaned using STATA 13, and then the analysis dataset was compiled using SAS version 9.4.

Sample

The sample consisted of patients admitted to the intensive care unit (ICU) at an academic medical center with Level 1 trauma center designation between January 1, 2008 and May 1, 2013 who met inclusion criteria. Inclusion criteria were admission to the adult surgical ICU or surgical cardiovascular ICU, either directly or following an acute-care stay. We included individuals younger than 18 years who were admitted to the adult ICU in an effort to include all patients admitted to the adult surgical or adult surgical cardiovascular ICU; however, we excluded patients with PIs present on admission to the ICU due to concern about misattribution of community-acquired PIs as HAPIs. Among individuals with more than one hospitalization during our study period, we included data from only the first hospitalization.

Measures

Variables were selected based on a combination of input from clinicians at our research site and the relevant literature. Predictor variables selected for our study are detailed in Table 6.1. Vital-signs data obtained from electronic monitors (peripheral capillary oxygen saturation and blood pressure) were included only if the low value was captured by three or more consecutive readings due to concern about spurious values that occur sporadically with continuous monitoring. The outcome variables were (a) a HAPI category 1–4, DTI, or unstageable PI, or (b) a HAPI category 2–4, DTI, or unstageable

Table 6.1

Predictor Variables

Variable	Mean (*SD*)	Range	Missing *N* (%)
Age	54 (19)	12-98	152 (2%)
Albumin (mg/dL) (minimum)	3.54 (0.81)	0.8–5.7	2557 (40%)
Body mass index (weight in kg/height in cm2) at admission	29.16 (9.6)	12.19-149.11	1423 (22.3%)
Creatinine (mg/dL) (Maximum)	1.7 (2.06)	0.31-52.7	20 (0.003%)
Glucose (mg/dL) (maximum)	178 (81.3)	52-1915	20 (0.003%)
Hemoglobin (g/dL) (minimum)	9.6 (2.36)	3.1-18.6	22 (0.003%)
Lactate (mg/dL) (maximum)	2.02 (2.24)	0.3-29	1474 (23%)
Prealbumin (mg/dL) (minimum)	13.4 (6.9)	3-40.1	5928 (93%)
Surgical time (minutes)	287 (235)	0-366	0
Variable	Category or Score *N* (%)		Missing *N* (%)
American Society of Anesthesiologists severity-of-illness score (maximum score)	1. 43 (0.7%) 2. 241 (3.8%) 3. 958 (15%) 4. 673 (10.6%) 5. 69 (1.1%) 6. 10 (0.2%)		4382 (68.7%)
Confusion assessment method	Delirious 491 (7.7%) Not delirious 2347 (36.8%) Unable to assess 125 (2%)		3413 (53.5%)
Fever ≥38º Celsius	Fever: 767 (12%) No fever: 5595 (87.8%)		7 (0.001%)
Hypotension: Mean arterial pressure <60 mmHg	Hypotensive: 2184 (34.3%) Not hypotensive: 4186 (65.7%)		7 (0.001%)
Glaslow Coma Score (lowest score)	3: 861 (13.5%) 4: 15 (0.2%) 5: 27 (0.4% 6: 86 (1.3%) 7: 111 (1.7%) 8: 111 (1.7%)	9. 98 (1.5%) 10: 305 (4.8%) 11: 150 (2.4%) 12: 19 (0.3%) 13: 84 (1.3%) 14: 317 (5%)	3379 (53%)

Table 6.1 (Continued)

Variable	Mean (*SD*) Range Category or Score *N* (%)	Missing *N* (%)
Glaslow Coma Score (lowest score) (continued)	15: 813 (12.8%)	
Peripheral capillary oxygen saturation	Oxygen saturation <90%: 964 (15.1%) Oxygen saturation >90%: 5405 (84.8%)	7 (0.001%)
Riker sedation and agitation score (lowest score)	1: 686 (10.8%) 2: 441 (6.9%) 3. 504 (7.9%) 4. 1342 (21%) 5. 6 (0.1%)	3397 (53.5%)
Vasopressor medication: Received dopamine (any dose/duration)	Yes: 257 (4%) No: 981 (15.4%)	5138 (80.6%)
Vasopressor medication: Received epinephrine (any dose/duration)	Yes: 73 (1.1%) No: 1165 (18.3%)	5138 (80.6%)
Vasopressor medication: Received Norepinephrine (any dose/ duration)	Yes: 695 (10.9%) No: 543 (8.5%)	5138 (80.6%)
Vasopressor medication: Received vasopressin (any dose/ duration)	Yes: 10 (0.2%) No: 1228 (19%)	5138 (80.6%)
Vasopressor medication: Received Phenylephrine (any dose/ duration)	Yes: 23 (0.4%) No: 1215 (19.1%)	5138 (80.6%)

Note. mm Hg = millimeters of mercury; mg/dL = milligrams per deciliter; *SD* = standard deviation; g/dL = grams per deciliter.

PI. We included category 1 PIs in our first outcome variable because PIs at the earliest stage are reversible, and therefore early recognition of this category is ideal (Halfens et al., 2001). We excluded category 1 PIs from our second outcome variable due to concern about nurses misidentifying transient redness as a category 1 PI (Bruce, Shever, Tschannen, & Gombert, 2012).

Analysis

Data Processing

We performed all analysis using R version 3.3.2 via the R Studio interface (version 1.0.136; R Core Team, 2013). First, we examined relationships among the available predictor variables and identified (through QR decomposition of the matrix of predictors) a potential linear combination of variables that kept the variable matrix from being of full rank. After identifying "vasopressin infusion" as the problem, we removed "vasopressor infusion" and the set of predictors was restored to full rank. Next, we looked for patterns of missingness and determined that the data were not missing completely at random by applying Little's (1988) "missing completely at random" test within the R package "BaylorEdPsych" ($P<0.0001$). Because data were not missing completely at random, we utilized multiple imputation (using the R package "Amelia"; Honaker, King, & Blackwell, 2011), an approach that imputes missing values while allowing for a degree of uncertainty; for example, a multiple imputation algorithm may code missing gender as "80% likely to be male" instead of simply "male" (Li, Stuart, & Allison, 2015).

Model Creation

We divided our data into training (67%) and testing (33%) datasets using the R package "caTools" (Tuszynski, 2015) and developed an RF algorithm via the R package "randomForest" (Breiman & Cutler, 2015) on the training data set for each of the two outcome variables (HAPI ≥category 2 and ≥category 1). We determined that "4" was the best number of features to be used for each tree (where M = total number of features and m = best number of features for each tree, $m = \sqrt{M}$ or $4.47 = \sqrt{20}$ [rounded to 4]). We determined that the optimal number of iterations (or trees in the forest) was 500, because after that value the estimated "out-of-bag" error rate was sufficiently stabilized. We included all of the predictor variables except vasopressin, and sampled cases with replacement. We set the cutoff value at 0.5 so that each tree "voted" and a simple majority won. After building the model with the training set, we applied the algorithm to the data in the testing dataset. Next, we used the R package "randomForest" (Brieman & Cutler, 2015) to rank variable importance; we then constructed visual representations of variable relationships to assess directionality. Finally, we used the R package "ROCR" (Sing, Sander, Beerenwinkel, & Lengauer, 2015) to assess receiver operating characteristics curves (ROC) and the area under the curve for each of our models using the testing data set. Because ROC curves can overestimate an algorithm's performance in a skewed data set, we also assessed precision-recall curves, which are useful in data sets like ours where classes are not evenly distributed (in our case, PIs were a rare outcome).

Results

Sample

The query produced 7,218 records. We omitted 841 records due to incomplete patient identification (ID; examples include a date instead of an ID or single digit numbers). The final sample therefore consisted of 6,376 patients admitted to the adult surgical ICU or adult cardiothoracic ICU. The mean age was 54 +/- 19 years. There were 2,403 females (38%) and 3,924 males (62%); gender data were missing for 49 individuals. The majority of the sample was White (*n* = 4,838, 78%). The mean length of stay was 10 (+/- 12) days (range 1–229 days).

Predictor and Outcome Variables

Two hundred and eighty-three individuals (4.4%) developed PIs of category 2 or greater, and 476 (7.5%) developed PIs of category 1 or greater. Frequency data for predictor variables are presented in Table 6.1.

Predictive Model: Category 1 and Greater Pressure Injuries

We developed an RF to predict category 1 and greater PI development among critical-care patients. Our first RF utilized data in our training data set; in this RF, our out-of-bag (OOB) estimate of error rate was 4.58%, indicating that 95.42% of the time, our OOB samples correctly categorized the patient according to PI outcome. Next, we applied the RF algorithm to our testing data set. Our algorithm performed similarly with an OOB estimate of error rate of 4.2%. Our model sensitivity and specificity were 40% (95% CI 0.37–0.43) and 100% (95% CI 0.99–1.0), respectively. The model positive predictive value (PPV) was 0.98 (95% CI 0.96–0.99) and the negative predictive value

(NPV) was 0.95 (95% CI 0.95–0.96). We used the testing data set to fit the Receiver operating characteristic (ROC) curve and the precision-recall plot. Figure 6.1 presents the ROC curve and Figure 6.2 presents the precision-recall plot. The area under the curve (AUC; also called the C-statistic) for the ROC curve was 0.9 (95% CI 0.88–0.92), whereas the area under the curve for the precision-recall plot was 0.79.

Figure 6.3 identifies the mean decrease in accuracy (MDA) for each variable. The MDA is measured by removing the association between a predictor variable and the outcome variable and determining the resulting increase in error. The MDA does not describe discrete values, so we also constructed visual representations to assess directionality. The most important variables in our analysis were, in descending order, low hemoglobin, longer surgical duration, lower body mass index, older age, higher glucose, lower albumin, higher creatinine, and higher lactate.

Predictive Model: Category 2 and Greater Pressure Injuries

We developed an RF to predict category 2 and greater PI development among critical-care patients. Our first RF utilized data in our training data set; in this RF, our OOB estimate of error rate was 2.72%, indicating that 97.28% of the time, our OOB samples correctly categorized the patient according to PI outcome. Next, we applied the RF algorithm to our testing data set. Our algorithm performed similarly with an OOB estimate of error rate of 2.87%. Our model sensitivity and specificity were 41% (95% CI 0.37–0.45) and 100% (0.99–1.0), respectively. The model PPV was 0.97 (95% CI 0.94–0.99) and the NPV was 0.97 (95% CI 0.97–0.98). We used the testing data set to evaluate the ROC curve and the precision-recall plot.

Figure 6.4 presents the ROC curve and Figure 6.5 presents the precision-recall

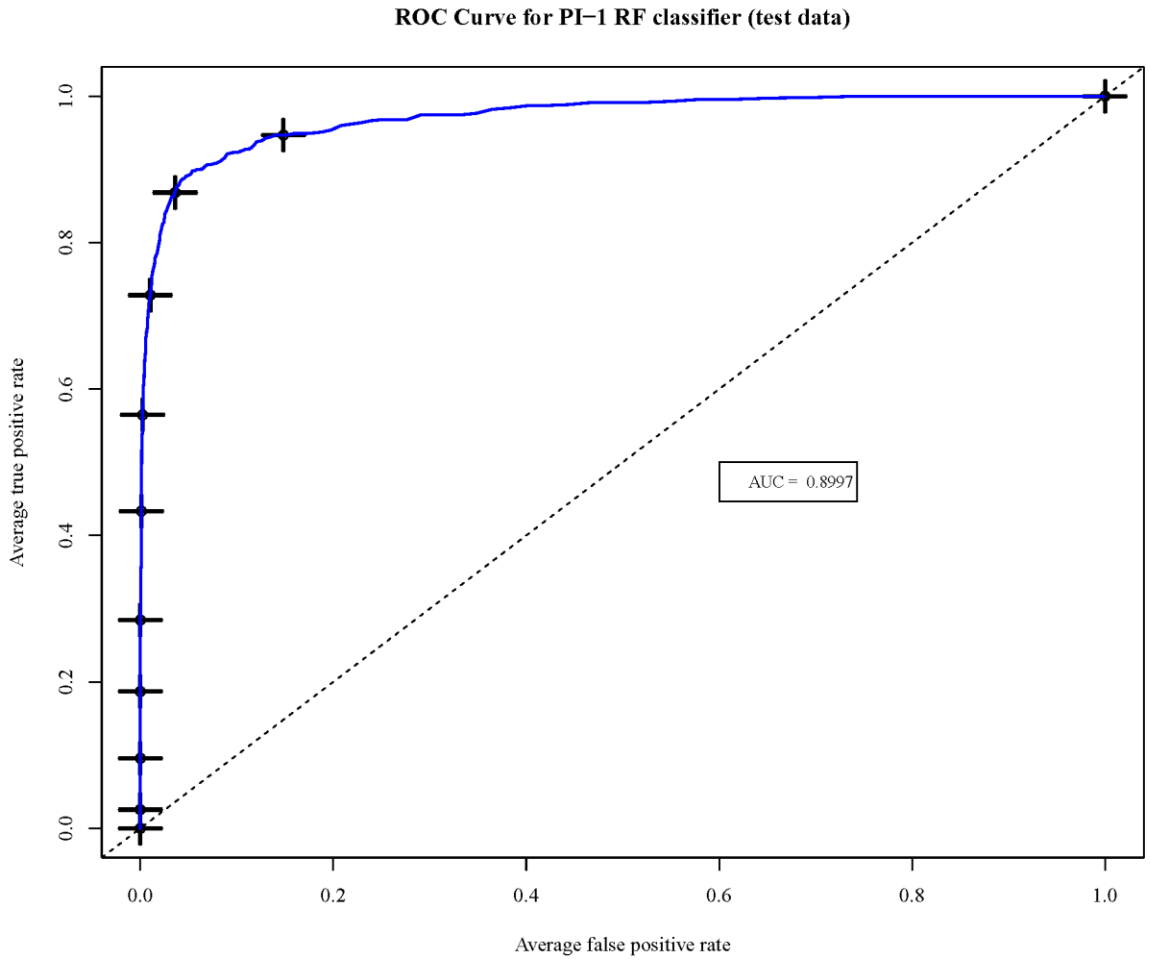

Figure 6.1 Receiver operating characteristic curve category 1 and greater.

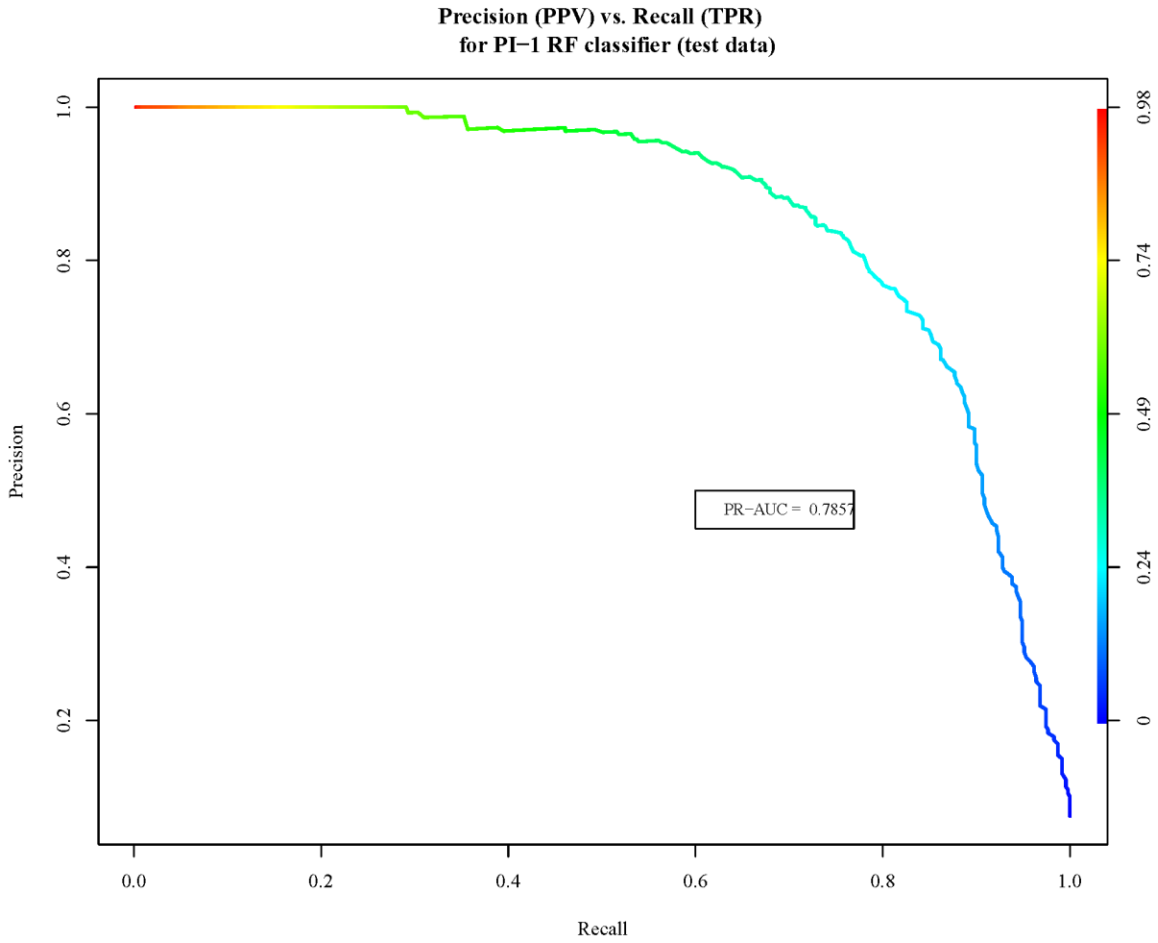

Figure 6.2 Precision-recall plot category 1 and greater.

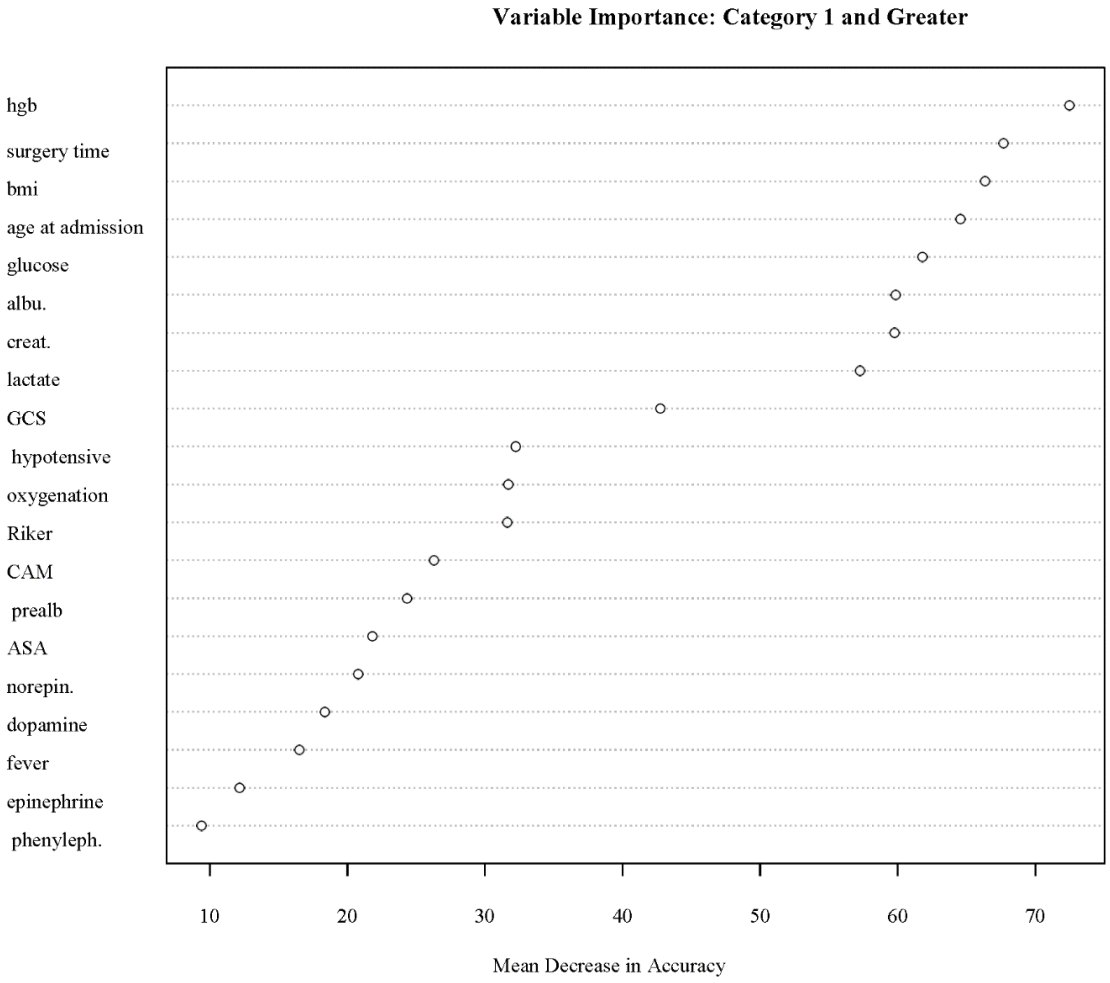

Figure 6.3 Variable importance category 1 and greater.

Note. Key: hgb = hemoglobin; bmi = body mass index; albu. = albumin, creat. = creatinine; GCS = Glaslow Coma Scale; Riker = Riker sedation and agitation scale; CAM = confusion assessment method; prealb = prealbumin; ASA = American Society of Anesthesiologists severity-of-illness scale; norepin. = norepinephrine; pheyleph. = phenylephrine.

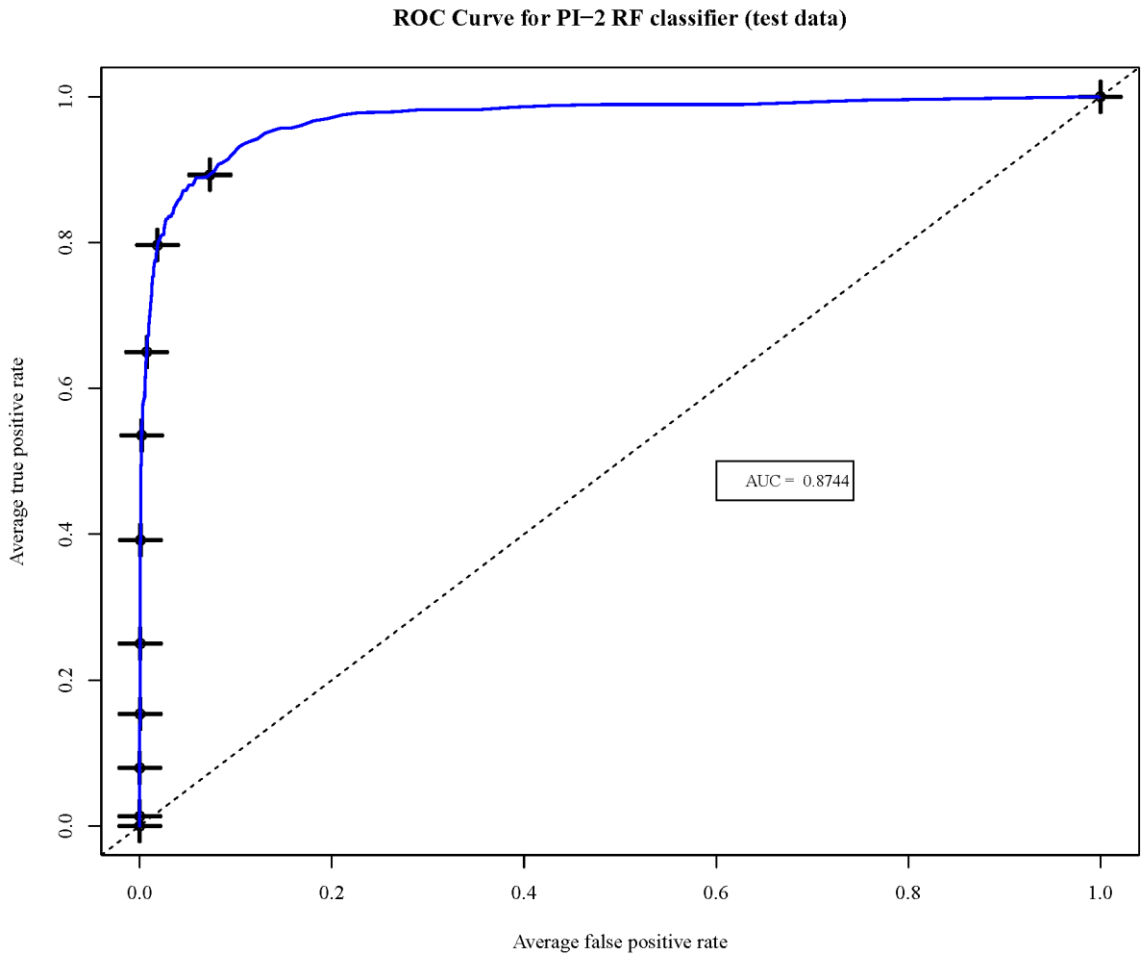

Figure 6.4 Receiver operating characteristic curve category 2 and greater.

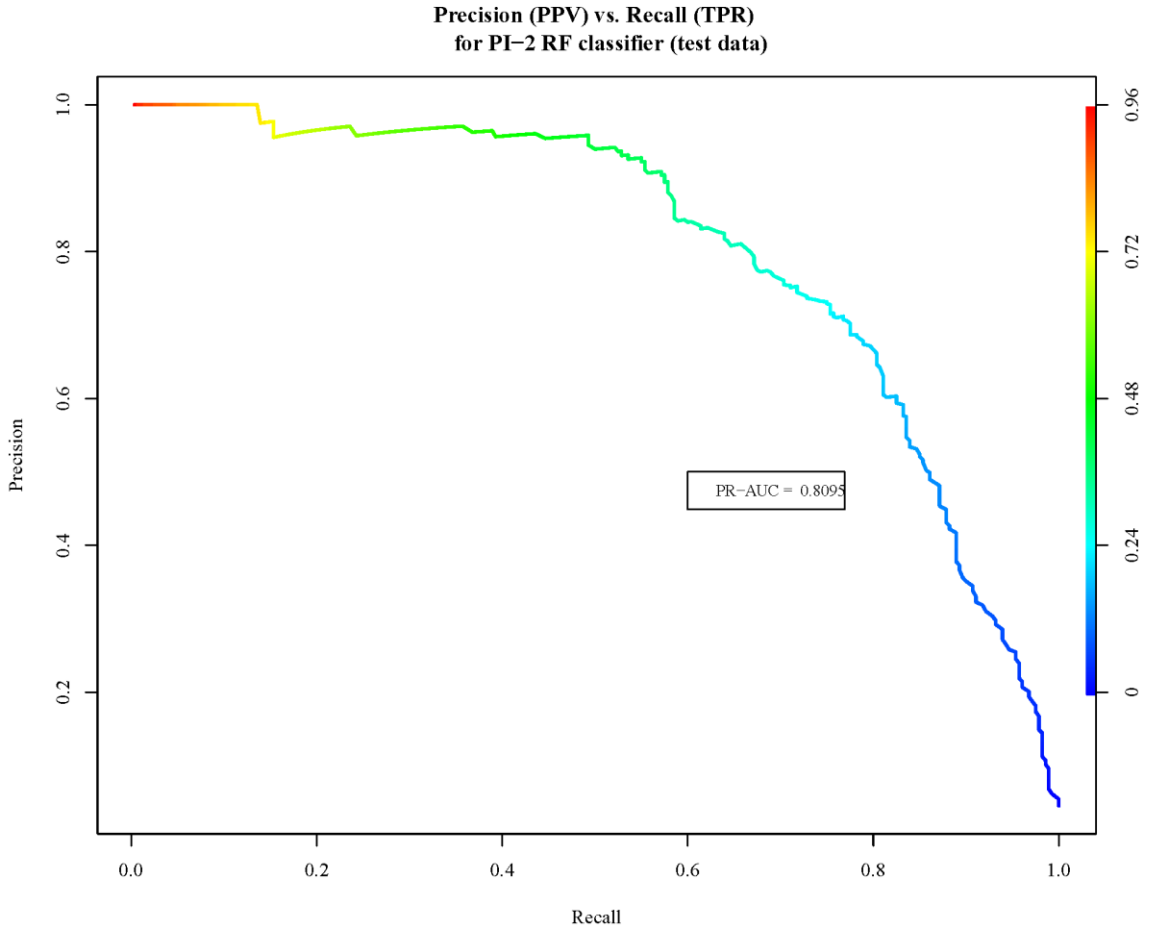

Figure 6.5 Precision recall plot category 2 and greater.

Figure 6.6 identifies the mean decrease in accuracy (MDA) for each variable. The MDA does not describe discrete values, so we also constructed visual representations to assess directionality. The most important variables in our analysis were, in descending order, longer surgical duration, lower hemoglobin, higher creatinine, older age at admission, higher glucose, lower body mass index, and lower albumin.

Limitations

We excluded individuals with PIs on admission in an effort to avoid misclassifying community-acquired PIs as hospital acquired. This may have introduced bias because people with preexisting PIs are at increased risk for PI development (NPUAP, EPUAP, & PPPIA, 2014). In addition, we were unable to access some variables that may be important for PI development in the EHR. Specifically, we were unable to obtain nursing skin assessments (general skin condition, edema, moisture) and treatment-related data (surfaces and repositioning schedules).

Although we used held-out data to test our model, validation with an unrelated clinical sample, such as patients from a different hospital system, is still needed. When the model is deployed in a different clinical sample it will likely require calibration due to population-related differences (for example, our Level 1 trauma center population is generally younger than a surgical critical-care population at a nontrauma center).

Discussion

This is the only study of which we are aware that utilizes machine learning to predict PI development among critical-care patients. We applied the RF technique, which is a particularly efficient use of big data because bootstrap replicates are used to train

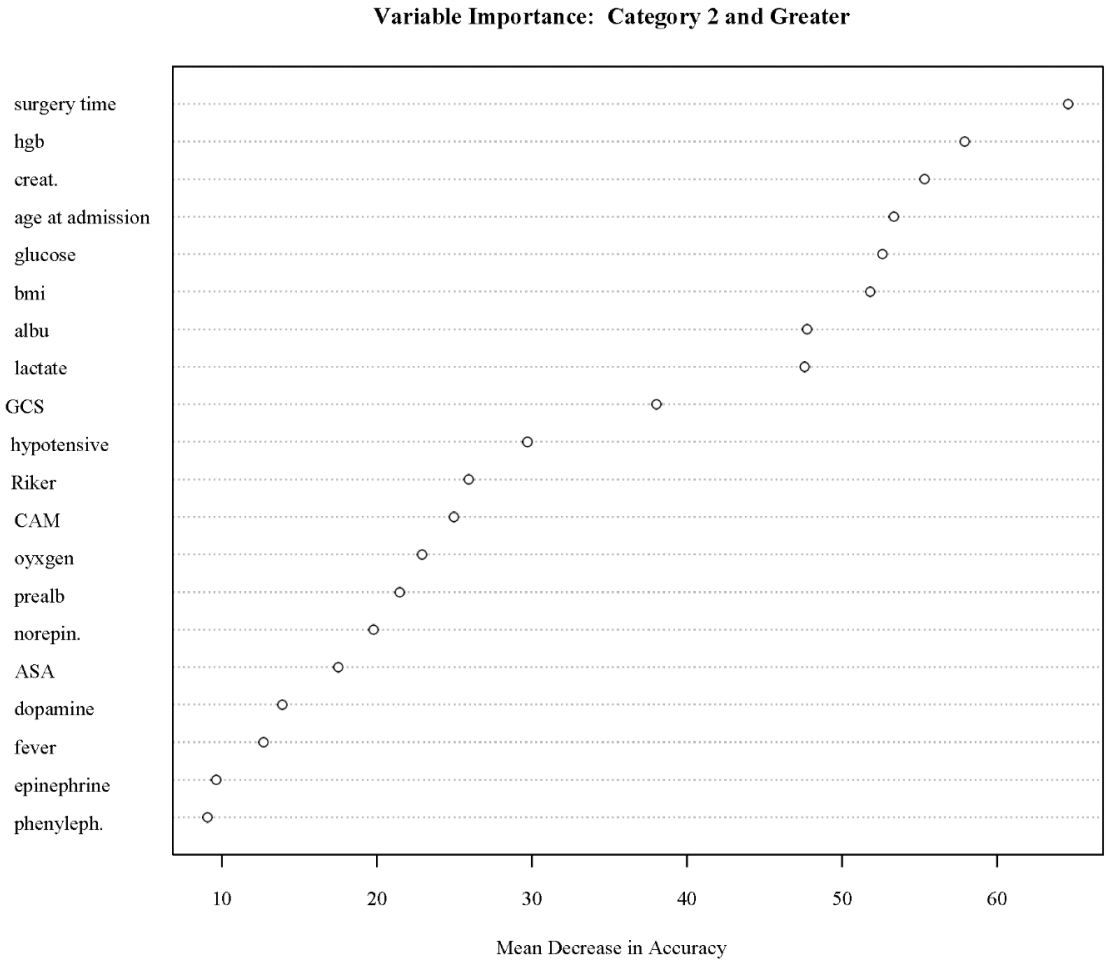

Figure 6.6 Variable importance category 2 and greater.

Note. Key: hgb = hemoglobin; bmi = body mass index; alb. = albumin; creat. = creatinine; GCS = Glaslow Coma Scale; Riker = Riker sedation and agitation scale; CAM = confusion assessment method; prealb = prealbumin; ASA = American Society of Anesthesiologists' severity-of-illness scale; norepin. = norepinephrine; pheyleph. = phenylephrine.

each classifier (Raju et al., 2015). RF is also advantageous because it is robust when confronted with missing data, which is a common problem in clinical data obtained from an EHR (Garge et al., 2013; Guidi et al., 2013). In addition, RF is relatively unaffected by moderate correlations among variables, which is important because correlations among clinical variables are common in health research, and excising correlated variables can result in data destruction that introduces bias (Harrell, 2010). Our held-out data (testing data set) lend additional strength to our study because we tested our data in an independent sample.

Our model performance results provide an interesting illustration about predictive statistics and ROC curve performance in the setting of skewed data. The ROC curve describes a model's ability to differentiate positive and negative cases at different sensitivity and specificity thresholds, where sensitivity is plotted on the y axis and specificity on the x axis (Lasko, Bhagwat, Zou, & Ohno-Machado, 2005). The area under the curve (AUC) describes a model's discriminatory power; a perfect AUC = 1.0 and random chance is 0.5. Our models both demonstrated good discrimination, with AUC values of 0.9 for PI $\geq$category 1 and 0.87 for PI $\geq$category 2 (Harrell, 2010).

Although the ROC curve is the standard way to present results for binary decision problems in machine learning, some authors contend that the AUC from the ROC curve is overly optimistic in skewed data sets where the number of negative examples greatly exceeds the number of positive examples (as in our data set, where the PI outcome variable was rare). The precision-recall curve is the same as the ROC curve on the y axis (although instead of sensitivity, the y value is labeled "recall"), but on the x axis the precision-recall curve plots precision instead of specificity. Precision compares false

positives to true positives instead of true negatives, which quantifies the effect of a large number of negative outcome variables (as in our data set; Table 6.2). When we applied the precision-recall plot to our data, our model's performance was somewhat depressed compared to the ROC data with an AUC of 0.79 (vs. 0.9 for the ROC curve) for the category 1 and greater PI outcome and an AUC of 0.81 (vs. 0.87 for the ROC curve) for the category 2 and greater PI outcome.

One way to consider our model's performance is to place our results alongside the Braden Scale. The Braden Scale is the most commonly used PI risk-prediction tool in North America and measures cumulative risk for PIs via seven categories: sensory perception, activity, mobility, moisture, nutrition, and friction/shear, with total scores ranging from 9 (very high risk) to 23 (very low risk; Braden & Bergstrom, 1987). Some studies have shown poor differentiation (specificity) when the Braden Scale is used in a critical-care population. Cox and colleagues (2011) evaluated the Braden Scale's predictive validity in a critical-care population and determined that at a cutoff score of 18, sensitivity was 100% while specificity was only 7%—meaning that although the Braden Scale correctly identified the patients who developed PIs, it had very limited ability to differentiate the individuals who actually went on to develop a PI from those who did not. It is worth noting, however, that 18 is a conservative value for being at risk, and that a more aggressive value might result in better differentiation among patients. The authors of another study found similar results: At a cutoff score of 18, sensitivity was 98% and specificity was 15%; however, at a cutoff of 13 (which lent the best AUC, at 0.68), the sensitivity was 78% with 46% specificity (Sookyung et al., 2013). In comparison to the Braden Scale, at 98% sensitivity, our model (for the outcome category

Table 6.2

Confusion Matrix for Pressure Injury Category 2 or Greater

Value	No Pressure Injury (Number)	Pressure Injury (Number)	Total (Number)
Test positive	False positive: 6	True positive: 232	238
Test negative	True negative 12,024	False negative: 337	12,361
	Total non-PI 12,030	Total PI 569[2]	

Calculations based on the confusion matrix:

Sensitivity	True positive/true positive + false negative	$\frac{232}{232+337}$= 0.4077
Specificity	True negative/true negative + false positive	$\frac{12024}{12024+6}$= 0.9995
Recall (same as sensitivity)	True positive/true positive + false negative	$\frac{232}{232+337}$= 0.4077
Precision	True positive/true positive + false positive	$\frac{232}{232+6}$=0.9748

Note. Numbers are based on the imputed data set; therefore, raw numbers are larger but prevalence is the same.

2 and greater) presents 72% specificity, whereas at 78% sensitivity, our model presents 98% specificity. Our model's relatively strong performance (AUC = 0.87 vs. 0.68 for the Braden Scale) suggests it would be a useful way to differentiate among critical-care patients to apply preventive measures that are not feasible for every patient due to cost, such as specialty beds.

The variables that were deemed most important based on the mean decrease in accuracy were (in descending order) longer surgical duration, lower hemoglobin, higher creatinine, older age at admission, higher glucose, lower body mass index, and lower albumin. We should avoid overinterpretation of these results because the importance of a variable within the model depends not only on the variable itself but also on its complex relationship with other variables in the data set. With that in mind, however, our variable importance results were generally consistent with the NPUAP, EPUAP, and PPPIA (2014) conceptual framework, which asserts that PIs are caused by a combination of mechanical boundary conditions and the susceptibility and tolerance of the individual.

Our data set contained two variables that are broadly in the "mechanical load" category as well as the "susceptibly and tolerance of the individual" category: surgical time and low body mass index (BMI). Surgery presents a mechanical boundary problem due to positioning and surface restrictions in surgery; low BMI enhances bony prominences. In addition, all of the variables deemed important, including surgical time and low BMI, have a direct effect on tissue tolerance: surgery imposes physiologic stress; low hemoglobin decreases oxygen-carrying capacity; higher creatinine denotes kidney failure, which affects fluid balance and severity of illness in general; higher glucose imposes inflammation; low BMI may represent undernourishment or frailty; and albumin

is an indirect indicator of nutrition status and is also important in perfusion due to colloid osmotic pressure. Age was also an important variable, possibly due to a combination of aging-related physiologic changes such as loss of skin elasticity and effects of comorbidities such as cardiac disease, which are more common among older people (Dharmarajan, Sipalay, Shyamsundar, Norkus, & Pitchumoni, 2000).

The variables that were not deemed important according to the MDA are also informative. Perfusion is theoretically a key concept in PI development because skin cannot survive without delivery of oxygen-rich blood (NPUAP, EPUAP, & PPPIA, 2014). In our analysis, variables related to perfusion, including vasopressor infusions, oxygenation, and hypotension, were not identified as important according to the MDA. However, ours was a single-measure approach, and therefore limited. It is possible that variables related to perfusion are better captured by a longitudinal approach, which would capture the dynamic effects of hemodynamic instability. Future researchers may consider a survival RF approach, which would take into account repeated measures related to perfusion.

Conclusion

We used an RF to predict PI development among critical-care patients. We developed models to predict category 1 and greater PIs and category 2 and greater PIs. The models demonstrated good discrimination, with the area under the curve of 0.9 (95% CI 0.88–0.92) and 0.87 (0.85–0.9) for $\geq$category 1 and $\geq$category 2 PIs, respectively (Harell, 2010). A major strength of our study was the use of a held-out data set, so that the algorithm was trained on one data set and tested on another.

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CHAPTER 7

RESULTS AND CONCLUSION

The purpose of this dissertation was to (a) conduct a systematic review of the literature to identify independent risk factors for pressure injury (PI), (b) use longitudinal analysis to identify the hazards of developing a PI based on changing Braden Scale total and subscale scores, and (c) develop a PI prediction model. This chapter will provide a brief summary of the individual studies' methods, results, and conclusions, followed by a synthesis of strengths, limitations, and implications across Chapters 4, 5, and 6.

Study Summaries

Systematic Review

The purpose of our systematic review was to identify risk factors independently predictive of PI (also known as pressure ulcer) development among critical-care patients. We based our approach on standardized criteria. A research librarian coordinated the search strategy and we searched the following databases: CINAHL (EBSCOhost), the Cochrane Library (Wilson), Dissertations & Theses Global (ProQuest), PubMed (National Library of Medicine), and Scopus. There was no language restriction. Articles that potentially met inclusion criteria were screened by two investigators. Among the articles that met selection criteria, one investigator extracted data and a second investigator reviewed the data for accuracy. Based on a literature search, we developed a

tool for assessing study quality using a combination of currently available tools and expert input. We used the method developed by Coleman and colleagues (2013) to generate evidence tables and a summary narrative synthesis by domain and subdomain.

We reviewed 1,753 abstracts; 158 were identified as potentially eligible and 18 fulfilled eligibility criteria. Five studies were classified as high quality, two were moderate quality, nine were low quality, and two were of very low quality. Mobility/ activity, age, and vasopressor infusion emerged as important risk factors for PI development, whereas results for risk categories that are theoretically important, including perfusion (apart from vasopressor infusion), nutrition, and general health status, were mixed. Methodological limitations across studies limited the generalizability of the results, and future research is needed, particularly to elucidate risk conferred by altered nutrition, perfusion, and skin/PI status.

Results from our review underscore the importance of avoiding overinterpretation of a single study, and the importance of taking study quality into consideration when reviewing risk factors. Maximal PI prevention efforts are particularly important among critical-care patients who are older, who have altered mobility, or who are receiving a vasopressor infusion.

Interestingly, in contrast to the systematic review, in our random forest (RF) model, vasopressor infusion and other variables related to perfusion (hypotension and poor oxygenation) were ranked as unimportant variables according to the mean decrease in accuracy, which is determined by temporarily removing a variable from the model and testing model performance without that variable. However, our approach was limited by its single-measure design (we used a single dichotomous measure for vasopressor

infusion: yes/no). It is possible that variables related to perfusion would be better represented by a longitudinal approach that would capture the dynamic effects of hemodynamic instability. Note that it is important to avoid overinterpreting results related to a variable's mean decrease in accuracy because that measure describes a variable's importance in the model based on complex interactions with other variables; it is not meant a stand-alone test of a variable's effect.

In contrast to the perfusion-related variables, the variable "albumin," which is indirectly related to nutrition status and informs perfusion via colloid osmotic pressure, was deemed an important variable according to the mean decrease in accuracy in our RF. Even though it was a single measure (minimum value in mg/dL during intensive care unit [ICU] stay), albumin was also important in terms of the mean decrease in accuracy in an RF developed to predict PI development in a general population (Raju, Su, Patrician, Loan, & McCarthy, 2015). However, in the Raju et al. (2015) study, instead of using imputation, the authors deleted all subjects who were missing serum albumin (753 of 1,635; 46%). Deleting those subjects may have introduced bias, because serum albumin is typically drawn if there is a reason to evaluate albumin (generally concern related to nutrition status, perfusion/colloid osmotic pressure, or to investigate low serum calcium because calcium is bound to serum proteins, specifically albumin). Because albumin is drawn in patients with a certain clinical profile, it is likely that albumin was not completely missing at random in the study conducted by Raju and colleagues.

Despite the limitation in handling missing data in the aforementioned study, albumin does appear to be worth further investigation in terms of its association with PI development in critical-care patients. Coleman and colleagues (2014) developed a

conceptual schema of proposed causal pathways for PI development in a general population based on the literature and expert opinion; within the framework, the authors hypothesize that albumin is a key indirect causal factor in PI development in that it is a driver of poor perfusion due to decreased colloid osmotic pressure among individuals with low serum albumin. Thus, the authors speculated that negative effects of low albumin are less related to poor nutrition (although they acknowledged that poor nutrition informs albumin status) and are more indicative of perfusion status (Coleman et al., 2014).

Braden Scale

The purpose of the Braden Scale (Braden & Bergstrom, 1987) study was to examine the risk of developing a PI associated with Braden total and subscale scores in a surgical critical-care population, and to ascertain whether the risk represented by the subscale scores is different between older versus younger patients. We identified a cohort of 6,376 surgical critical-care patients via EHR data to determine Braden Scale total and subscale scores, age, and incidence of PI development. We used survival analysis to determine the hazards of developing a PI associated with each subscale of the Braden Scale, with the lowest risk category as a reference. In addition, we used time-dependent Cox regression with natural cubic splines to model the interaction between age and Braden Scale scores and subscale scores in PI risk.

Of the 6,376 ICU patients, 257 (4%) developed a PI (category 2–4, deep tissue injury (DTI), or unstageable injury) and 516 (8%) developed a hospital-acquired pressure injury (HAPI) of any stage. With the exception of the friction and shear subscales, regardless of age, individuals with scores in the intermediate risk levels had the highest

likelihood of developing a PI. Risk associated with age varied among Braden subscales. In the activity, moisture, and nutrition subscales, older people with midrange or higher severity scores were more likely to develop a PI than younger people with the same scores.

The finding that, with the exception of the friction/shear subscale, individuals with scores in the intermediate risk levels had the highest likelihood of developing a PI, was unexpected. We speculate that nurses noted the patients at most severe risk and applied maximal preventive measures, which effectively prevented some PIs from occurring among individuals in the highest risk categories, whereas patients with moderate risk scores may not have received the same level of vigilance. Therefore, we recommend that maximal preventive measures should be extended to include individuals with intermediate Braden Scale subscale scores, and that age should be considered as a factor in care planning, particularly among older individuals with midrange or higher severity scores in the activity, moisture, and nutrition subscales.

Our Braden Scale results were interesting in that it appeared that preventive interventions aimed at Braden high-risk patients were actually effective at preventing PIs among Braden high-risk critical-care patients, although we cannot confirm this hypothesis because we do not have treatment data. This was totally unexpected. In fact, we initially sought to develop a predictive model specifically because studies show that the Braden Scale demonstrates relatively poor performance in critical-care populations due to low specificity (poor differentiation). In a recent study conducted among critical-care patients at a Braden Scale cutoff score of 18 (“at risk”), sensitivity was 98% and specificity was only 15%. A cutoff of 13 lent the best discrimination, with an area under

the curve of 0.68 with 78% sensitivity but still only 46% specificity (Sookyung et al., 2013). The area under the curve of 0.68 is not ideal, as values <0.8 are considered insufficient in terms of their utility for differentiating among outcomes (Harrell, 2010).

So why does the Braden Scale appear to "work" in terms of cueing nurses to identify high-risk patients but also fail to show adequate discrimination on the receiver operating characteristic (ROC) curve? One possibility is that the Braden Scale is actually an effective clinical intervention in the sense that nurses are adjusting their care based on Braden Scale values and preventing PIs. After all, "risk" means a person might develop a PI, and at least some PIs are preventable. Perhaps the Braden Scale is correctly identifying high-risk patients and nurses (and other healthcare providers) are doing an effective job at intervening for Braden high-risk patients.

It is also possible that different PI etiologies exist and that the Braden Scale is good at recognizing one type of high-risk patient (specifically, one with some combination of low mobility, low activity, poor nutrition, high moisture, altered sensory perception, and risk for friction and shear). Our systematic review determined that other factors, including age and vasopressor infusion, are also important in PI development, and the broader PI literature increasingly implicates general health status, perfusion, and skin status (including prior PI development) as important in PI etiology (National Pressure Ulcer Advisory Panel [NPUAP], European Pressure Ulcer Advisory Panel [EPUAP], & Pan Pacific Pressure Injury Alliance [PPPIA], 2014).

The possibility that different etiologies exist is supported by our model's strong performance (area under the curve = 0.87) relative to the performance of the Braden Scale in another study (area under the curve = 0.68; Sookyung et al., 2013). Our model

was primarily focused on physiologic values that influence the susceptibility and tolerance of an individual's skin, whereas the items included in the Braden Scale are a combination of factors related to pressure and repositioning (mobility, activity, and sensory perception), friction, and moisture; only a single Braden Scale item, nutrition, is purely intrinsic (Braden & Bergstrom, 1987). Although PI etiology is clearly multifactorial, it is possible that some PIs are influenced primarily by external factors such as pressure, repositioning, or moisture, and can therefore be prevented by carefully adjusting care based on Braden Scale parameters (which may explain the relatively low area under the curve), whereas other PIs may be primarily caused by intrinsic factors such as general health status, oxygen-carrying capacity (hemoglobin), or aging-related changes in tissue tolerance. Combinations of intrinsic factors may be considered a unique etiology which, for a few patients, may even translate into an unavoidable PI or one that cannot be prevented with available preventive measures (Black et al., 2011; Wallis, 2010).

Predictive Model

The purpose of the final study in this dissertation was to develop a model to predict PI development among critical-care patients via a machine learning/RF approach. We chose a machine learning approach to build our predictive model because machine learning techniques can effectively and efficiently utilize large amounts of clinical data that are routinely collected in EHRs (Raju et al., 2015). Among machine learning approaches, we selected RF, an ensemble method similar to a decision tree, where random subsets are drawn from the data with replacement (Raju et al., 2015). The advantages of an RF approach are that (a) all of the data can be used for training and

validation while avoiding the decision-tree tendency to overfit the model, and (b) the approach is relatively robust in the face of multicollinearity and missing data (Garge, Bobashev, & Eggleston, 2013; Guidi, Pettenati, Miniati, & Iadanza, 2013).

Our primary outcome variable was development of a category 2 or greater PI. The RF that we developed to predict category 2 our greater PI demonstrated an out-of-bag (OOB) estimate-of-error rate of 2.72%, indicating that 97.28% of the time, our OOB samples correctly categorized the patient according to PI outcome. Next, we applied the RF algorithm to our testing data set; our algorithm performed similarly with an OOB estimate-of-error rate of 2.87%. The area under the ROC was 0.9 and 0.87 for the outcome variables ≥category 1 PI and ≥category 2 PI, respectively. The most important variables in our analysis, based on the mean decrease in accuracy were, in descending order, surgery time, hemoglobin, creatinine, age at admission, glucose, body mass index, albumin, and lactate. Our model's area under the curve (0.9 for PI ≥category 1 and 0.87 for PI ≥category 2) demonstrated greater than adequate ability to discriminate between patients in terms of PI development (Harell, 2010); therefore, clinicians may consider using our model to direct interventions such as specialty beds that are not feasible for most patients.

Study findings related to variable importance based on the mean decrease in accuracy were consistent with findings from our systematic review in terms of age as an important risk factor, but for other risk factors the mean decrease in accuracy does not reflect the findings from our review. Specifically, findings related to perfusion (hypotension and oxygenation) and vasopressor infusion were unexpected in that vasopressor infusions, hypotension, and poor oxygenation were relatively unimportant in

our model based on the mean decrease in accuracy. As noted above, the mean decrease in accuracy is not intended to be a stand-alone test of a variable's importance because it reflects complex relationships among variables. Even so, it is interesting that vasopressors are actually the least important variables in our model according to the mean decrease in accuracy. A major reason for this might be our analysis strategy: We dichotomized vasopressor infusion as a yes/no variable and failed to identify dose or duration, both of which are important factors in terms of receptors activated and physiologic response. More research is needed to quantify the effects of vasopressor infusion, and we recommend that our results be considered alongside our significant methodologic limitation in vasopressor variable operationalization.

Insights Across Studies

Strengths

The most important strength of our systematic review was our careful quality analysis. We designed a quality-assessment framework based on currently available tools and expert input. Two researchers independently conducted quality appraisal and reached "substantial" agreement independently, as evidenced by Kappa = 0.72 (Viera & Garrett, 2005). Findings from our review underscored the importance of quality appraisal. One of the articles that met inclusion criteria had major methodological limitations but was cited 56 times in the SCOPUS database, primarily based on the clinically important finding that more days without nutrition was associated with more PIs (Eachempati, Hydo, & Barie, 2001). In that study, however, the data presented in tables and the associated odds ratio indicate the opposite: that days without nutrition was a *protective* factor. That paradoxical result of an association of days without nutrition and lack of PI development

was actually replicated in the bivariate analysis conducted by Slowikowski and Funk (2010), but the authors did not enter nutrition in the multivariate analysis because they thought it might have been a spurious finding.

Our database studies share a strength in their large, comprehensive data set (N = 6,376). In addition, the longitudinal approach that we applied in Chapter 5 represents a strength for that study. Prior studies used a Braden Scale measurement from a single point in time or averaged the measures in some way, which failed to capture the dynamic nature of a critical-care patient's physiologic status. In contrast, our approach, time-varying Cox regression, took into account all of the Braden Scale measurements.

Our analysis strategy represents a strength in our predictive model study. Ours is the only study of which we are aware that utilized machine learning to predict PI development among critical-care patients. We applied the RF technique, which is a particularly efficient use of big data because bootstrap replicates are used to train each classifier (Raju et al., 2015). RF is also advantageous because it is robust when confronted with missing data, which is a common problem in clinical data obtained from an EHR (Garge et al., 2013; Guidi et al., 2013). In addition, RF is relatively unaffected by moderate correlations among variables, which is important because correlations among clinical variables are common in health research, and excising correlated variables can result in data destruction that introduces bias (Harrell, 2010).

Limitations

Our systematic review was limited in its scope in that we did not perform subgroup analysis to identify critical-care patients in studies of general hospitalized patients. In addition, although we did not have a language requirement, our database

search was conducted in databases that are commonly used for English-language research. It is likely that relevant studies in other languages exist and were not captured by our search strategy.

Results from our database studies (Braden Scale and predictive model) have limited generalizability due to our use exclusively of surgical critical-care unit and cardiovascular ICU populations. Prior population-based studies have shown that surgical critical-care patients are at higher risk for PI than medical critical-care patients; it is not yet known which factors or combinations of factors inform the increase in risk (Nijs et al., 2009; O'Brien, Shanks, Talsma, Brenner, & Ramachandran, 2014).

An important limitation in both of our database studies (Braden Scale and predictive model) is the lack of data related to preventive measures and treatments. Clearly, PI risk is affected by the patient's physiologic status, but risk is also influenced by the measures clinicians take to ameliorate risk. The lack of preventive treatment information is an important caveat for our Braden Scale results: We only speculate that individuals with midrange Braden Scale severity scores received less-intensive treatment than those with high-risk scores. It is also possible that some third (unmeasured) factor actually accounted for a greater share of PI risk than the items included in the Braden Scale. For example, the Braden Scale does not address perfusion as a driver of PI, and it is also possible that individuals with midrange risk encompassed a disproportionate number of people with altered perfusion. Decompensated heart failure is a condition that alters perfusion and that clinically presents as a person with midrange Braden Scale findings (e.g., a person who can get into a chair but cannot walk well, one who can eat a little but is not well nourished, etc.).

Another limitation that our database studies share is that we excluded individuals with preexisting PIs out of concern that community-acquired PIs would be misrepresented as HAPIs in our data set. It possible that in doing so, we introduced bias by excluding some high-risk patients. The NPUAP, EPUAP, and PPPIA's (2014) conceptual framework contends that skin status and prior PI development is an important risk factor in subsequent PI development.

Finally, our predictive model study is limited by its single-measure approach. Because we did not employ a longitudinal analysis, our study did not capture the dynamic nature of a critical-care patient's physiologic status, particularly as it applies to hemodynamic measures such as blood pressure, oxygen delivery, and vasopressor infusion.

Implications

Research Implications

We noted several implications for future research. First, all of the PI studies conducted among critical-care patients that we identified share our predictive model's single-measure limitation. This is important, because critical-care patients are by definition unstable and at risk for physiologic deterioration. A longitudinal approach is needed to capture dynamic changes in critical-care patients' physiologic status.

In addition, future researchers should consider including category 1 PIs in research aimed at identifying risk factors for PIs because category 1 PIs are reversible without permanent tissue damage (Halfens, Bours, & Van Ast, 2001). Among the studies included in our review, three studies did not report PI categories, six studies designated a PI as ≥category 1, seven studies included only PIs that were ≥category 2, and two studies

included separate models for PIs ≥category 1 and ≥category 2. Interestingly, the studies that included both outcomes (≥category 1 and ≥category 2) generated similar models and results regardless of the outcome variable designation (Cox, 2011; Tayyib, Coyer, & Lewis, 2015). This was also true in our database studies: Results for the category 1 and greater outcome were very similar to results for the category 2 and greater outcome in our Braden Scale paper (Chapter 5) and in our predictive model (Chapter 6). This is interesting, because it points to common etiology between category 1 and category 2 (and worse) PIs, and underscores the importance of recognizing PIs at their earliest and within the most reversible category (category 1).

As noted in the limitations section, we excluded individuals with preexisting PIs from our analysis. Although this practice is common (in an effort to avoid misidentifying community-acquired PIs as HAPIs), it is not ideal, because the researchers are then unable to assess risk associated with prior PI development (or more broadly, skin status), and those with prior PI may be more prone to developing PI in the hospital. Future researchers should avoid excluding patients with preexisting PIs if possible, and research to quantify the risk for PI associated with prior alterations in skin integrity is needed.

Practice Implications

The most important direct practice implication from this dissertation was the finding that individuals with midrange Braden Scale total and subscale scores were more likely than individuals with high-risk Braden Scale scores to develop PIs. We speculate that nurses were cued by more severe scores to apply maximal preventive measures for individuals with the most severe risk scores. Additional study including treatment factors is needed, but in the meantime nurses may consider extending maximal preventive

interventions to patients with midrange severity Braden Scale findings. In addition, because older people with midrange or higher moisture, activity, and nutrition subscale scores were more likely than younger people with the same scores to develop PIs, age should be considered along with Braden Scores as a factor in care planning. For example, an older person with moderate levels of moisture might benefit from the aggressive moisture-management interventions intended for patients of all ages with more severe levels of skin moisture.

Education Implications

Our systematic review determined that most PI studies were of low quality, which is consistent with a prior review conducted in a general population (Coleman et al., 2013). Our findings revealed inconsistent results among studies, as well as marked variability in study quality, indicating that researchers and clinicians should avoid overinterpretation of results from any single study, and underscoring the importance of teaching clinicians the skills needed to assess study quality—particularly in terms of evaluating sources of bias or potential bias. Nursing journal clubs are a particularly effective evidence-based strategy to teach clinicians (and researchers) to critically evaluate the literature (Lachance, 2014).

Policy Implications

The most important policy implication from our study is related to the data we failed to obtain. The Research Data Service (RDS) team initially determined that the data could be obtained with moderate difficulty; however, according to the RDS team, the variables required for this project represented some of the most comprehensive and

challenging variables ever requested from the Service. The variables that were most problematic (and that we ultimately were unable to obtain) were from data that nurses produce: positioning information, nurses' skin-care assessments, and incontinence and skin-care interventions. Our difficulty in accessing nursing data is symptomatic of a larger problem: The data nurses produce and record in the EHR are rarely used to their full potential (Westra et al., 2015).

In order to produce sharable, comparable data, the information nurses produce must be standardized, or coded in an organized structure to represent nursing knowledge (American Nurses Association, 2015). Currently, care organizations are not well incentivized to utilize standardized nursing data because current incentive payments for meaningful-use standards do not include most nursing-derived data (Westra et al, 2015). Because federal mandates do not extend to nursing-derived data, it is especially important for nurses themselves to advocate for inclusion of American Nurses Association-approved standardized nursing terminologies by supporting nursing representation in information technology decision making at their home institution and in state and national policy decisions (Alderden & Cummins, 2016).

Although standardization is a necessary first step toward harnessing nursing data to improve patient care, it not sufficient. Sharing data in a secure way is complex and requires careful attention to prevent a loss of confidentiality (Westra et al., 2015). Most importantly, the home institution where the data are produced, or a clinical data repository, must be willing to store and maintain nursing data. Nurses should advocate for inclusion of nursing-derived data in data warehouses and clinical data repositories so that the valuable, patient-level data nurses produce can be used to improve patient care.

Conclusion

The purpose of this dissertation was to (a) conduct a systematic review of the literature to identify independent risk factors for PI, (b) use longitudinal analysis to identify the hazards of developing a PI based on changing Braden Scale total and subscale scores, and (c) develop a PI prediction model. Our systematic review determined that age, activity/mobility, and vasopressor infusion were important factors in PI development among critical-care patients. Results from our predictive model, which demonstrated greater than adequate discrimination with an area under the curve of 0.9 and 0.87 (for category 1 and greater PI and category 2 and greater PI, respectively), were inconsistent with our systematic review results in terms of the importance of vasopressors. Vasopressors were unimportant variables based on our model's mean decrease in accuracy values. The unexpected lack of importance for vasopressors may be because our single-measure approach failed to adequately operationalize the vasopressor variables. Findings from our Braden Scale study were also unexpected: We discovered that patients with midrange Braden Scale and subscale severity scores (excepting friction and shear) were more likely than patients with high-risk Braden Scale scores to develop PIs. More information related to treatment measures is needed, but in the meantime we recommend that nurses consider extending maximal preventive interventions to individuals with midrange Braden Scale scores. Overall, results from our systematic review and data base studies underscore the complex and multifactorial nature of PI development.

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