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Title: Real-Time, Wireless, Networked Feedback for Bed-Tilt Compliance

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Determining Bed-Tilt Compliance with a Wireless Sensing System and Bedside Feedback

Structured Abstract

Purpose: Ventilator-associated pneumonia, a common nosocomial infection, has been shown to occur less frequently when the head-of-bed angle (HOBA) is maintained between 30 and 45 degrees. Our team developed and deployed a novel, real-time, wireless sensing system to track HOBAs of ventilated hospital patients. We utilized the data to determine rates of compliance, causes for noncompliance, and methods for raising protocol adherence.

Scope: A review of bed-angle compliance studies suggests that less structured and controlled observations produce higher compliance rates. A portable sensing system offers an objective tool to continuously monitor and report bed angles over a sustained period of time without human-recorded logs or charts.

Methods: Following a 1-week pilot study, HOBA monitors were placed on 20 patient beds over a 3-week experimental period. Then, 83,655 bed-angle samples were recorded over 1,579 hours and compared with staff-recorded bed angles. The final experiment acquired 224,000 angle records to measure the effectiveness of HOBA feedback at the bedside.

Results: The monitoring system found an average HOBA of 27.34 degrees—a compliance rate of 35.8%. Noncompliant angles slightly less than the desired angles, or slips, accounted for 55.9% of all HOBAs. Long periods of low-HOBA, or lapses, accounted for only 7.1% of the angles. Bedside feedback improved compliance rates from 41.3% to 64.5%.

Key Words: Protocol adherence, monitoring, head-of-bed, ventilator-associated pneumonia, wireless sensors, bedside feedback

Purpose: Ventilator-associated pneumonia (VAP) is a disease commonly acquired by patients receiving breathing assistance while in intensive care. The disease is expensive to treat and sometimes fatal. One known practice for reducing the likelihood of contracting VAP is to maintain the patient's head-of-bed angle (HOBA) between 30 and 45 degrees. Existing research on the frequency with which the HOBA is maintained within such a range shows, by and large, a lack of even minimum compliance. Thus, to measure compliance rates, we developed a reliable system for obtaining objective bed-angle measurements for intubated patients. Because studies report varying compliance rates, it is difficult to discern whether or not healthcare workers are consistently performing this simple yet crucial task. We set out to create and distribute a novel wireless sensing system to independently attain bed-angle measurements for intubated patients. With this information, we then sought to pursue two specific aims. First, we aimed to discover the root causes of HOBA noncompliance by analyzing data provided by the bed-tilt sensors. Second, we sought to determine the efficacy of bedside feedback in raising bed-tilt compliance rates. Our original third aim, to understand how HOBA feedback at the nurse's station would change healthcare worker behavior, was dropped once the first experiment made it clear that situations in which healthcare workers forget to raise the bed after performing patient activities occur so rarely that it was unlikely we would find a significant effect in an experiment of the size proposed. It is our hope that these aims will bring the scientific community a step closer to lowering healthcare costs for both hospitals and patients with regard to VAP. We also hope this will constitute a critical step toward reducing the amount of time patients spend in intensive care.

Scope: Ventilator-associated pneumonia (VAP) is a common infection acquired in intensive care units (ICUs).[1] In a study of 1,658 mechanically ventilated patients in 27 European ICUs, 23.7% of the patients developed VAP.[2] A review of 429 research papers shows crude VAP mortality rates of between 24% and 50%, reaching 76% for specific settings and infection by high-risk pathogens.[3] Ventilated ICU patients with pneumonia have a 2- to 10-fold higher risk of death versus patients without pneumonia.[4] The financial costs of VAP are also striking. When Rello et al. (2002) compared patients who developed VAP to control subjects without VAP, they found that the VAP patients stayed on ventilation longer, stayed in the ICU longer, and had longer hospital stays.[5] The VAP patients incurred average hospital charges of $104,983 compared with $63,689 for non-VAP patients.[5] Another study in Canada found that VAP accounts for approximately 17,000 ICU days per year or around 2% of all ICU days.[6]

The lungs are typically sterile, but an invasion of bacteria via aspiration can lead to pneumonia.[7] All patients supported by mechanical ventilation (without tracheotomy tubes) are intubated with endotracheal tubes. These endotracheal tubes have the potential to serve as a conduit for transferring secretions into the lungs. Endotracheal tubes also decrease important host defense mechanisms, such as mucociliary function and coughing reflex.[7] Furthermore, colonized endotracheal tubes can further increase the risk of bacterial aspiration.[7] Drakulovic et al. (1999) observed that intubated patients who were completely flat (0°) had significantly higher VAP and mortality rates than those patients with a head-of-bed angle (HOBA) elevated to 45 degrees.[8] Largely motivated by this study, the American Thoracic Society, the Infectious Disease Society of America,[9] and the Canadian Association of Medical Microbiology and Infectious Diseases[10] all issued recommendations to position ventilated patients in a semi-recumbent position with bed backrest elevation set between 30° and 45°.

Despite these guidelines, previous studies have found that patients' beds are rarely elevated to 30°, let alone 45 degrees.[11] A PubMed literature search performed in December 2014 with the MESH keyword "Pneumonia, Ventilator-Associated" and "bed" yielded 133 articles. A review of these and related articles either citing or cited by these revealed just 19 English reports in which bed angles were directly monitored as part of the primary study. These studies are summarized in Table 1 below. In this table, compliance is indicated by the percentage of measurements with HOBA above 30°, unless otherwise noted. Although Drakulovic's work is the basis of standard protocol, published attempts to validate and extend his work[11-13] have been unsuccessful because of the difficulty of maintaining proper bed-angle protocol. The failure of these studies to maintain HOBAs makes it difficult to learn more about Drakulovic's findings and casts doubt on whether the protocol is being followed in regular hospital settings.

Table 1: Published Experiments Specifically Monitoring Head-of-Bed Angles Ordered by Maximum Compliance Range

Study	**Sample Size**	**Sampling Technique**	**Results**
Sedwick et al. 2012[14]	4,709 ventilator days	Reviewed patient chart	100% compliance after education bundle implemented
Teixeira et al. 2013[15]	2,472 patients over 2 years	Checklist filled out during rounds	97% compliance
Bird et al. 2010[16]	Intubated patients in large hospital over 31 months	Twice-daily observation by respiratory care specialist	65-99% compliance
Croce et al. 2013[17]	630 patients	Evaluated once per day by member of the research team	83.3-91.5% compliance
Lawrence and Fulbrook,2012[18]	315 observations	Once-per-week observation	80-88% compliance
DuBose et al. 2008[19]	570 patients	ICU fellow filled out checklist daily	35.2-84.5%, after intervention
Bingham et al. 2010[20]	100 patients	Direct observation of VAP procedures during 2-hour interval	70-72% compliance
Williams et al. 2008[21]	268 measurements made over the course of 2 weeks	Daily observations by researcher using angle indicator	23% compliance before intervention, 71.5% after
Rose et al. 2010[22]	141 patients	Measured 3 times per day by research team member	32-70% compliance
Lyerla et al. 2010[23]	315 observations on 43 patients	Direct observation of angle indicator by researcher 1-3 times daily	44% compliance before intervention and 67% compliance after intervention
Wolken et al. 2012[24]	7,720 hours of ventilated patient observations	Continuously monitored electronically	61% compliance (hrs > 30 degrees) without feedback, 76% compliance with feedback

Bouadma et al. 2010[25]	1,649 ventilator days over 4 weeks	6 observations/day of a bicolored plastic ribbon attached at the head of the bed to indicate appropriate elevation	5-58% compliance
Sasabuchi et al. 2012[26]	12 patients, 265 intubated hours	Hourly for 24 hrs by electronic bed monitor	24% compliance before intervention; 45% compliance after
Grap et al. 2005[13]	276 ventilator days	Continuous	28% compliance
Liu et al. 2013[27]	2,842 ventilator days.	4 times daily at 5- to 7-hr intervals; measurement made by physician, corroborated by attending nurse	27.8% compliant
van Nieuwenhoven et al. 2006[11]	109 patients	Continuous	15% compliance (defined as > 45 degrees)
Markewitz et al. 2005[28]	30 patients	Continuous	3% compliance
Balonov et al. 2007[12]	29 patients	Automatically every 20 minutes	Effectively 0%
Laux et al. 2010[29]	24-bed trauma unit	Electronically monitored	Novel definition of compliance (more than 16 hrs/day above 30 degrees). Compliance between 3 hrs and 16 hrs/day

Reviewing the studies in Table 1, it would appear that the less structured and controlled the observations, the higher the perceived compliance rate. For example, Sedwick et al.'s 2010 analysis of patient charts suggested a 100% compliance rate after an educational intervention.[14] In a study by Bird et al. that measured HOBA compliance twice daily over 3 years, compliance rates increased from 57-82% in 2007 to 77-100% in 2009.[16] A large-scale implementation of the VAP bundle of 112 ICUs with 550,800 ventilator days published self-reported HOBA compliance, with lapses cited as the primary reason for noncompliance.[20] The studies near the bottom of the table that include automatic monitoring tend to have much lower compliance rates than those reported in studies in which human observations are used. A clear visual presentation of the angle seems to improve compliance. Rose et al. (2010) found that an inclinometer mounted on the bed improved HOBAs so that they were in compliance 70% of the time rather than 32% without the inclinometer.[22] Another study by Williams et al. found similar compliance increases and attributed this benefit to the increased visibility of the angle.[21]

Failure to achieve full compliance with bed-angle recommendations, particularly compliance with the 30- to 45-degree position, may be caused by: (i) contraindications to raised elevations; (ii) nursing concerns; and/or (iii) human error. Rose et al. noted a contraindication rate of 14% in their 1,154-patient study.[22] The contraindications include hemodynamic instability, undergoing a medical procedure in the bed, intracranial hypertension, and intra-aortic balloon pumping. Nursing concerns may be another reason for not achieving the desired angle. A survey of nurses found that the most common reasons for not raising the bed were concerns that: (i) the patient would slide down in bed; (ii) it would be too difficult to rotate the patient laterally; (iii) the patient would not be comfortable; (iv) skin breakdown would occur; or (v) hemodynamic stability would be compromised.[30] The third reason, human error, relates to differences between intent and outcome. For example, the challenge of achieving the desired angle may be the result of having to guess at the HOBA visually. In a study of 160 nurses and trainees, 61.6% of the bed-rest angles were overestimated, compared with just 14.9% that were estimated accurately.[31]

Previous researchers have addressed bed-angle compliance from the viewpoints of knowledge and adherence,[32-35] visibility,[22] checklists,[19] and training.[36-38] To our knowledge, none have addressed the problem from the viewpoint of human error. The human error perspective requires the analysis of individual moments at which the desired behavior does not occur, which often leads to important insights into how to avoid such behaviors.[39-43] Immediate feedback may be effective in addressing some categories of human error.

Auditing and feedback have a long history in medicine and have been used successfully to modify behavior.[44] A meta-analysis on feedback effectiveness suggests that the most effective feedback: (i) provides a correct solution; (ii) delivers the information in writing; (iii) provides feedback to both the group and the individual; and (iv) delivers the feedback privately.[45] Other studies have suggested that feedback must be timely, individualized, and meaningful.[46] Effective feedback requires accurate measurement.

A portable sensing system can be deployed in a variety of environments to quickly provide a continuous report of bed angles over a sustained period of time lasting days or weeks. This, coupled with and linked to bedside devices that present a color-coded display of the current bed angle, allows for the assessment of HOBA maintenance. Such monitoring systems have proven to be essential because they provide a stream of data that can later be processed and analyzed—typically within the context of other available data—in order to more clearly understand and diagnose the root causes of a process issue. Such a system would allow bed angles to be studied in greater detail in order to determine which behavior patterns are most likely the causes for the lack of compliance.

Methods: Our study consisted of three separate experiments. The first experiment was a pilot experiment intended to test the consistency and stability of the magnetically adhered sensors. Once established, we then deployed the devices in a second, 3-week-long experiment in order to continuously monitor the HOBA for intubated patients in the ICU. A third experiment was conducted 1 year later in which a bedside display was mounted above the in-room computer, as it is a central focal point for healthcare workers in their daily activities.

The approach of our studies differs from past attempts (e.g., Grap et al. 2005 and Sasabuchi et al. 2012) in that it employs a device that is portable, battery-operated, and wireless (Fig. 1). These technical adaptations allow the monitor to be easily placed, observed, and retrieved without disrupting the workflow in the ICU.

Figure 1: To the left, a prototype of the bed angle monitor with: a) bubble level indicator, b) USB port, and c) LED indicators. To the right, the inside of the device revealing: d) two circuit boards, e) a rechargeable battery, and f) the magnet on the back cover.[47]

General Methods – The Sensor

A magnet affixes the sensor to the bed frame. The sensor periodically senses the angle of inclination at the head of the bed with its inclinometer. The inclinometer is connected to a microprocessor that both saves the readings and emits a silent, wireless broadcast that can be received and optionally displayed remotely (outside a patient room). The device (i) is easy to use and installs in seconds for each bed; (ii) weighs about 200 grams; (iii) can operate for 1 week without servicing; and (iv) has data that can be collected in an efficient manner, as each device is equipped with a radio.

The bed angle monitor design is based on a dual-axis, high-precision accelerometer chip (Analog Devices' adxl203ce) and a TelosB, a microprocessor/radio circuit that has been the core component in many of our past hardware designs.[48] The monitor also includes a custom-designed circuit board and case. The case has an embedded bubble level to ensure that the sensor is properly aligned when initially installing the device on the bed. The magnetic strip allows the device to be mounted on the bed frame, parallel to either the bed's long or short axis. In a week-long pilot experiment with 20 beds experiencing normal patient activity, we confirmed that the sensor placement was stable and consistent. The sensor's output is linearly related to the sine of the head-of-bed angle. To test the precision of the sensor output, a sensor was oriented at -50 to 50 degrees in increments of 10 degrees in two rotational dimensions. At each position, 20 reports from the on-chip analog-to-digital were collected and averaged, in a manner typical of the sensor's normal use. The experiment was repeated three times. The sensor values were then fit to the sine of the inclination angle. Calibration revealed that the R2 values for both the x and y regressions are very close to 1, indicating that more than 99.95% of the sensor variation is attributable to predictable changes in angle. The sensor's sensitivity is better than 1° in the range of 0° to 45° elevation. The same procedure was used to determine the slope and intercept between each sensor and the inclination angle.

A rechargeable cell phone battery powers the device, and the software is designed to use the battery power efficiently. The sensor's sampling frequency may be easily altered, but it is currently programmed to sample every 0.5 seconds and broadcast and store the measurements when either: (i) 5 minutes have elapsed since the last recording or (ii) the bed has moved since the last recording. In normal use, the device will operate at least 1 week between recharging. The data may then either be read wirelessly or downloaded directly from the device. A status light blinks every 7 seconds to indicate the sensor's battery and memory health; green represents all is well, red is when the memory is low or the battery is running out. The device is a core and novel component for achieving our specific aims.

Experiments 1 and 2 Methods

In the first experiment, a week-long pilot with 20 beds experiencing normal patient activity, we confirmed that the sensor placement was stable and consistent.

In the second experiment, conducted in September 2013, we deployed these devices on 20 patient beds in a medical intensive care unit at a large, Midwestern hospital for a continuous, 21-day interval. Twice each day, a doctor on the unit recorded which patients were intubated, what angles had been recorded for these patients' bed angle in the patient record by the nurses, and the ordered bed angle. The broadcasts from the tilt sensors were received by several tablet PCs placed near the nurse stations associated with the rooms under study. The nurses in the unit were aware of the experiment and the fact that the head-of-bed angle was being monitored, but they received no special instructions regarding how to position bed angles, as this was primarily a test of the data collection procedure and instrument rather than an intervention. The protocol was IRB approved.

To define intervals of approximately consistent bed angle, the bed-angle reports for each bed containing an intubated patient were resampled to produce a time series with a consistent, 1-second interval spacing. For seconds with more than one bed angle, available values were averaged. For seconds without bed-angle measurements, values were interpolated from the closest readings. Significant changes in bed angles were detected by convolving the time series with the vector [-1, -1, -1, -1, 1, 1, 1, 1] and dividing the sequence whenever the absolute convolved product was greater than 20, representing an event in which the average angle changed by greater than 20 degrees over a 4-second interval. Sub-intervals with lengths less than 300 seconds were discarded. The first and last 10 seconds were trimmed from the remaining readings.

The intervals are first divided into three groups: compliant, slips, and low-angle. Compliant intervals have an average angle greater than or equal to 30 degrees. Slips have an angle less than 30 degrees and greater than or equal to 15 degrees. The remaining, low-angle, intervals are again divided. Patient care intervals are low-angle intervals with durations less than 1,000 seconds. Lapses are low-angle intervals with durations longer than 1,000 seconds.

After initial analysis of bed-angle data, members of the research team not associated with the hardware development and deployment conducted semi-structured interviews with nurses and residents in the medical intensive care unit. The interview questions gathered information regarding: (1) providers' understanding and practice of setting and adjusting bed angles; (2) their initial impression on the bed-angle data presented to them; and (3) their reasoning on why the error-associated patterns in data occur. After gathering their comprehension/awareness about the bed-angle setting and adjustment process, the interviewers explained what the different error types, such as slips, lapses, and mistakes, mean, using plots of specific instances from the data set as examples. Participants were asked why those error-associated patterns might occur and what procedural and behavioral aspects might cause those errors. They were also asked for their perceptions on the frequency of such events. The interviews were audio recorded and transcribed. The participant comments were qualitatively coded with categories developed to describe reasons for error-associated patterns.

Experiment 3 Methods

The third experiment was conducted in the intensive care unit of a large, Midwestern hospital. Electronic bed-angle sensors were placed on all 22 beds in four of five ICU work areas. The four work areas were selected because they were most likely to host intubated patients. Each work area consisted of five to six beds. A tablet PC in each work area served as a redundant data backup, recording the wireless messages broadcast from each bed-angle sensor.

At the start of the experiment and as new patients were intubated during the experiment, a staff physician flipped a coin to determine whether or not a bed-angle display would be placed bedside. We mounted the bedside display above the in-room computer that nurses generally use to enter patient data while performing patient care activities. The bedside display was an Android application running on a Nexus 7 tablet. The tablet received the radio transmissions from the bed sensor with a radio connected to its serial port and both stores and displayed the value on the monitor. We mounted the tablet above the in-room computer with an adjustable mount designed to mount tablets to wheelchairs. The nurses often interact with the computer before and after performing patient care activities to check the patient record and to record information about the patient care activities, making it an ideal location for the reminder display.

The display received the bed angle broadcast from the bed-angle sensor and displayed the head-of-bed angle. The display was color coded: green when above 30 degrees and red when below 30 degrees. The bedside display remained in the room and operative until it was removed when the patient was extubated.

The experiment was conducted over a 38-day period. Before beginning the experiment, the unit staff was briefed on the protocol and the devices during three daily briefings, and this was supplemented by email. On day 19, the bed-angle sensors were each removed for several hours in order to recharge their battery. A staff physician kept a record of when each patient was intubated or extubated as well as a record of the doctor-ordered head-of-bed angle. This was in addition to the HOBAs that nurses recorded in the patient's electronic chart.

Results – Experiments 1 & 2

Experiment 1 confirmed the accuracy and stability of the bed-tilt sensors.

Experiment 2 yielded 1,579 hours of monitored bed angles of intubated patients and 83,655 angles produced by the bed-angle monitor. The doctor-ordered HOBA was 30 degrees for all these patients throughout the study. The medical records for these patients included 526 angles recorded by nurses and 83,655 angles produced by the bed-angle monitor.

The average bed angle reported by nurses was 30.7 degrees, with a standard deviation of 7.6 degrees. Ninety-five percent of the reports were for angles 30 degrees or above. The most commonly reported angle was 30 degrees, which accounted for 85.9% of all the reported angles. Except for four values, all the reported angles were multiples of 5 degrees.

The data contained 668 intervals, which accounted for 5,130,000 seconds, or 90.3% of the time during which intubated patients were studied. Figure 2 illustrates the results of reducing the raw data into intervals for a typical dataset. Across all the data, the average interval length was 7,685 seconds, and the average interval angle was 24.76 degrees. The time-weighted average interval head-of-bed angle was 27.34 degrees. The 432 intervals with an average angle less than 30 degrees accounted for 64.2% of the total interval lengths.

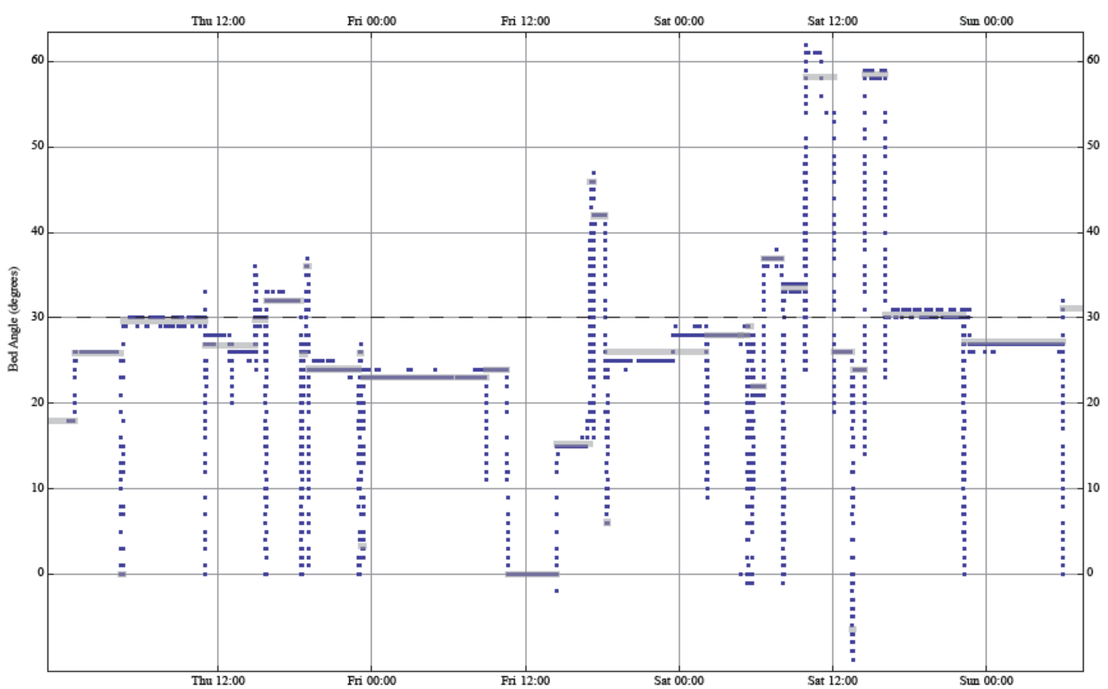

Figure 2. Reported head-of-bed angles in degrees for an intubated patient over a 3-day period. The horizontal dashed line indicates the doctor-ordered head-of-bed angle. The grey bars indicate the average angle for intervals, using the algorithm defined in the data processing section.[47]

Figure 3 plots each interval according to its duration and average angle, with the markers indicating the interval's category.

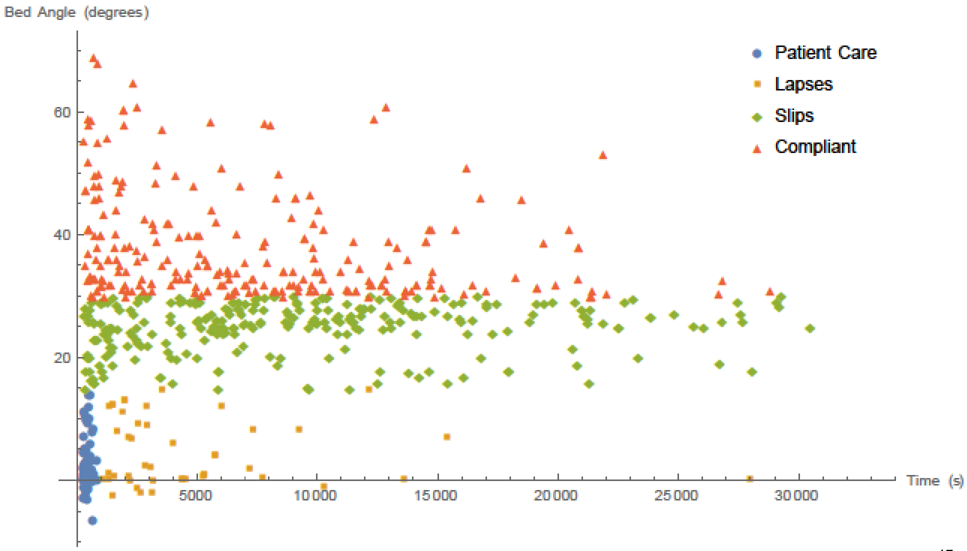

Figure 3. Plot of interval angles versus interval lengths, separated by interval category.[47]

There were 423 compliant intervals, 272 slips, 47 lapses, and 104 patient care intervals. Compliant intervals, lapses, slips, and patient care intervals accounted for 1,838,000 seconds (35.8%), 367,000 seconds (7.1%), 2,883,729 seconds (56.2%), and 45,254 seconds (0.9%), respectively. A naïve, one-sided sign test of all interval angles indicates that the median is significantly less than 30 degrees at the 5% level ($W(n = 668) = 243$, $p \leq 2\ 10{-}12$). A more generous definition of compliant intervals that accounts for potential rounding to 5 degrees, as indicated in the nursing charts, reduces the compliance threshold angle to 27.5 degrees. With this threshold, and eliminating the nursing care intervals, a one-sided sign test rejects the hypothesis that the median interval angles is less than or equal to 25.7 degrees at the 5% level ($W(n = 564) = 243$, $p < 5{*}10{-}6$). Figure 4 displays the detail of the interval angle versus interval length plot in the region near the patient care intervals. This graph reveals how modifying the patient care interval criteria would reclassify lapses and slips.

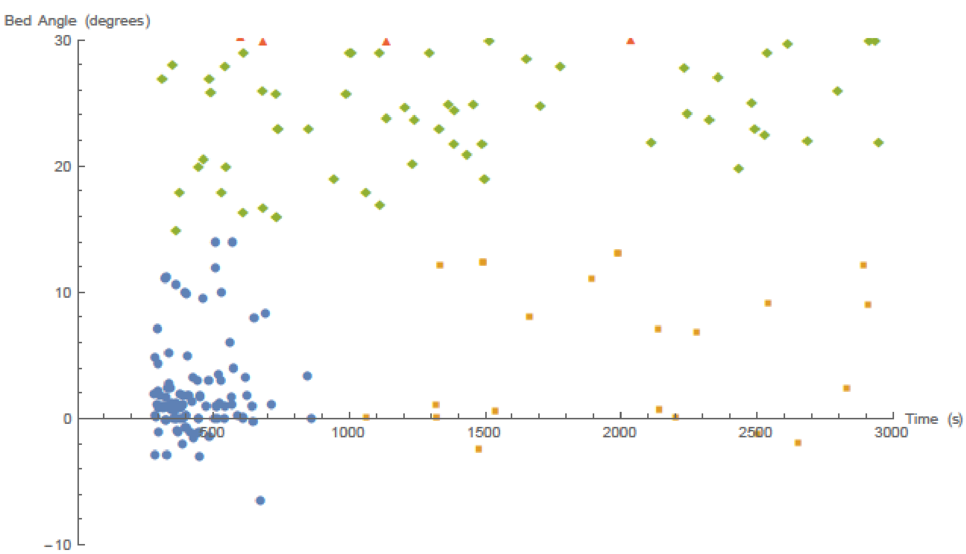

Figure 4. Plot of interval angles versus interval lengths near the region defined as patient care intervals, with the marker coding used in Figure 4.[47]

Figure 5 presents the histograms for the intervals, coded by interval category. The histogram suggests a bimodal distribution, with one peak near 30 degrees and another peak near zero degrees.

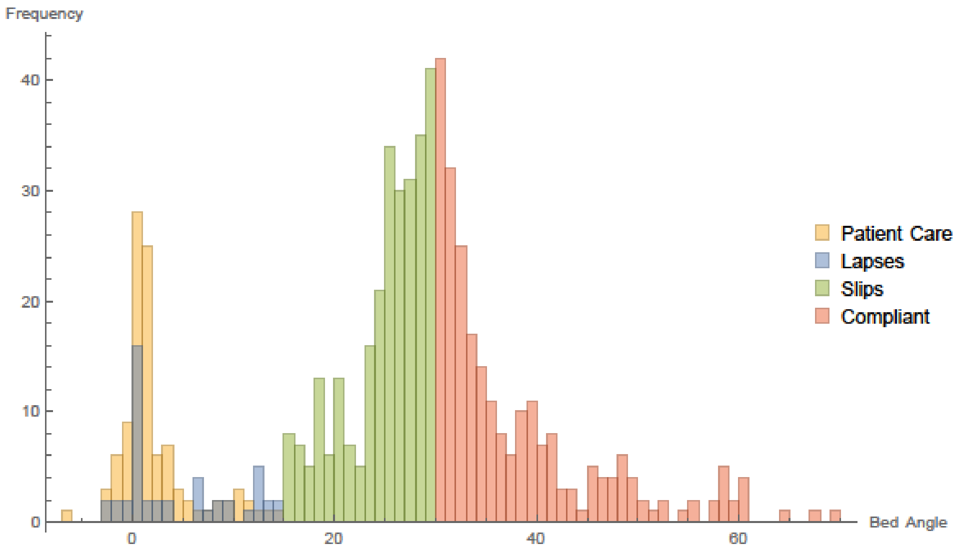

Figure 5. A histogram of the bed angles and frequency of occurrence for each interval.[47]

The qualitative analysis yielded a consistent explanation for the process of setting HOBA requirements. Typically, physicians initiate the patient head-of-bed order and route it to the nurses as part of a ventilator bundle. Nurses control the head-of-bed angle and chart the angle values every 4 hours. Nurses typically do not communicate with physicians when they lower the bed below ordered values. Nurses provided several reasons why the bed will be angled less than or greater than 30 degrees. Some of these are determined by patient condition and procedures being performed on patients, in concordance with or against physician orders. Multiple nurses and residents reported that angles 30 degrees and above prevent aspirations and ventilator-associated pneumonia, trading off from setting the angle to something less than 30 degrees, which prevents pressure ulcer formation.

Nurses reported that they may position a patient to less than 30 degrees to accommodate various patient medical conditions, such as patients who are hemodynamically unstable or who have suffered spinal trauma. The participants reported that such patients are unable to tolerate a high HOBAs. Nurses also suggested that the HOBA is lowered for certain procedures, such as bathing patients, cleaning beds, and inserting catheters. During these procedures, frequent interruptions occur and may cause personnel to leave bed angles out of compliance for longer durations than intended when they are called away and forget to return. Participants suggested that the repetition of the reported angles may be, at least in part, a result of copying chart values from previous patient records, particularly in intervals between staff changes and handoffs.

The purpose of experiment 2 was to measure bed angles for intubated patients to determine: (i) whether the measured bed angles agreed with the electronically reported bed angles; (ii) the frequency and magnitude of lapses and slips; and (iii) the pattern of bed-angle adjustments.

The average angle reported in the electronic medical record was 30.7 degrees, and the time-weighted measured angle was 27.34 degrees. Given that the annotations in the electronic medical record appear to be rounded to the nearest 5 degrees, some clinicians may not perceive this difference as practically significant. Nevertheless, the median value of the interval bed angles was significantly lower than 30 degrees. In fact, two thirds of the time when the bed is in a stable position, it is at an angle less than 30 degrees. Viewed another way, 95% of the reports in the electronic medical record indicate protocol compliance, whereas the continuous measurements indicate compliance only 35.8% of the time. To complicate the story, if the interval angles are analyzed in a manner that accounts for patient care intervals and allows for rounding of decimal places, there is no evidence to suggest that the median bed angle is significantly less than 30 degrees.

There are at least two analysis perspectives to understand the bed-angle data. From the first perspective, each time a health care worker adjusts the bed, he or she makes a decision about the appropriate angle at which to set the bed. This decision is either in compliance or out of compliance. From this perspective, the record of the average interval angles yields a tally of 423 compliant and 245 noncompliant decisions. From a second perspective, the health care worker distinguishes between short-term and long-term decisions, seeking to optimize the bed position over the course of the day, permitting short deviations for patient care activities while emphasizing long-term compliance. This perspective yields the conclusion that, although the bed angle was compliant only 35.8% of the time, the time-weighted average angle was fairly close to the desired bed angle. The first perspective emphasizes the moment of decision making, whereas the second perspective recognizes the need to occasionally reduce the bed angle for patient care, a perspective that forgives small, short-duration adjustments that occur over the course of the day. Thus, the second measurement approach is more appropriate for the clinical realities of patient care. Still, such a low compliance rate begs an explanation.

The values in the electronic medical record and the comments made in the interviews support the conjecture that the health care workers are aware of the desired bed angle. The primary reasons offered for consistently differing from the prescribed values are medical contraindications, which were excluded from the study. The other reasons for lowering the HOBA include patient care activities and concern for ulcer formation. Our analysis accounts for patient care activities, which have a relatively small effect on the time-averaged bed angle and compliance rate. The remaining concern is for ulcer formation. If this was a principal concern, however, it was not well represented in the interviews or in annotations found in patient records. Were slips or lapses the cause for the noncompliant angles?

Of the 668 intervals, 272 were classified as slips and 47 as lapses. Most of the time (56.2%), the beds were set at an angle categorized as a slip. Lapses accounted for only 7.1% of the bed setting time but had a disproportionately large impact on the time-weighted bed angle.

The interviews suggested that the slips might be caused, at least in part, by difficulties with the bed indicators. The rough symmetry of the graph reinforces the conjecture that the nurses' intention is to place the head-of-bed at or near 30 degrees, but this intention is acted upon imprecisely. Viewed as a stochastic distribution with a mean of 30 degrees, natural variance would cause the angle to be out of compliance as often as it is in compliance. However, the measurement variance of the central peak in Figure 5 seems larger than one would expect if the angle indicator was observed for each measurement. The large variance is more consistent with healthcare workers visually estimating the bed angle. Whatever the cause, the nominal compliance rate is generally dominated by slips. The specific degree to which this is true, however, depends on the manner in which slips, lapses, and patient care are defined.

The categories were defined by a series of demarcations. The first demarcates compliant angles from noncompliant angles. We considered both 30-degree and 27.5-degree thresholds. This choice has an important effect on whether the beds are found to be in compliance or not. The second demarcation is between low angles and slips. Here, we arbitrarily chose 15 degrees. Figure 4 illustrates the relative dearth of long intervals in this midrange, between 12 and 18 degrees, particularly for intervals longer than 1,000 seconds. Although the specific location of the angle is arbitrary, the existence of a division is indicated both by language in the interviews relating to "lowering the patient" and to a pattern in the observed data. The third demarcation is within the low-angle intervals. Again, Figure 4 suggests a clear cluster among short intervals and a sporadic sampling for longer intervals. This is consistent with the statement in the interviews that the beds are generally lowered briefly for patient care activities, but occasionally a nurse is distracted before he or she can raise the bed again. Although the cutoff of 1,000 seconds was arbitrary, the data suggest that any value between 800 s and 1,500 seconds would have yielded similar results.

The third objective of the study was to determine the pattern of bed-angle adjustments. Figure 5 suggests a bimodal pattern, with a central peak located at 30 degrees. A second peak near the origin tends to be populated by shorter intervals, as indicated in Figure 4. If the adjustments of bed angle were consistent in that the bed was lowered to close to zero and then raised up again, the size of the two peaks would be similar. The fact that the central peak is larger suggests that healthcare workers often change the bed position among raised angles. This pattern may be observed in several places in the sample data in Figure 2. However, Figure 2 reveals that the bed is most frequently lowered for a period shorter than the 300-second interval threshold and then raised to a higher level. These short deviations to lower angles would have increased the number of patient care intervals but would not have contributed substantially to the time-weighted average angles.

Assuming that stochastic variation around the target value is the primary source of error, at least two strategies would help correct the problem. The first strategy would be to increase the target angle. The official recommendations are for bed angles between 30 and 45 degrees. Rather than interpreting the target as 30 degrees, the nurses might target the middle of that range. For example, consider the effect of changing the target angle to 37.5 degrees. Assuming that the patient care activities were to remain consistent, increasing the remaining angles by 7.5 degrees would increase the frequency of adjustments to compliant angles from 40.1% to 78.2%. Thus, simply changing the target angle to the middle of the target range could have an important influence on the compliance rate.

A second strategy would be to use feedback, bed-angle indicators, or other technologies to remind the nursing staff to continue to raise the bed until the target angle was achieved. This would probably not affect the 47 lapses and 104 adjustments associated with patient care activities, but it would reduce the variance around the 30-degree peak or bias the distribution above the 30-degree mark. If that technology were perfectly consistent in eliminating slip errors, extrapolating our results suggests that the bed angle would have been compliant 80% of the time, or even 93% of the time, if exceptions were allowed for patient care activities. This is why we conducted a third experiment in which we sought to determine the efficacy of bedside displays in raising HOBA compliance.

Results – Experiment 3

During the study, 28 intubated patients were observed for intervals ranging from 12 hours to 38 days. The doctor-ordered HOBA for each of these intubated patients was 30 degrees.

Nurses recorded 605 HOBA entries in the patients' electronic medical records; 533 of these (88%) reports documented HOBAs of at least 30 degrees. Eight reports (1.2%) documented angles less than 30 degrees, and 34 reports (5.6%) documented angles greater than 45 degrees.

Approximately 1.9 million records were downloaded from the tilt sensors and tablets, 224,000 of which were related to time periods when an intubated patient was in bed.

The continuous electronic record of bed angles was divided into intervals of relatively stable bed angles, using the approach presented in experiment 1. Stable bed-angle intervals generally occurred between periods of rapid bed-angle change when, for example, a nurse adjusted the bed angle during the course of normal patient care activities.

These were then processed to reduce the data to a series of 512 intervals of stable bed angles, including 267 intervals with monitored patients and 245 with unmonitored patients. The intervals spanned 812.5 hours of observation for monitored patients and 715.6 for unmonitored patients. Figure 6 shows two typical 75-hour periods as the head of bed angles changed for two intubated patients. The deduced periods of consistent bed angle are indicated in this figure. Figure 7 plots the HOBA versus duration for each interval. The average bed angle in these intervals was 24.6 degrees for the monitored and 23.1 degrees for the unmonitored patients. Head-of-bed angles were compliant (greater than 30 degrees) 64.5% of the time in the monitored condition and 41.3% of the time in the unmonitored condition.

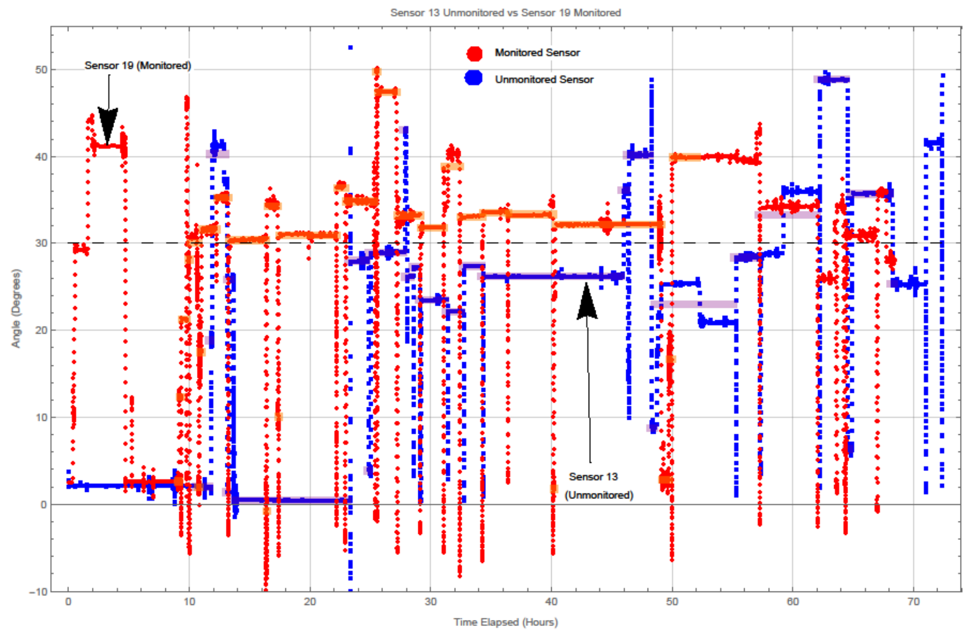

Figure 6. Typical bed head-of-bed angle patterns for with a bedside monitor (red) and without a bedside monitor (blue). The shaded bars indicate intervals of consistent bed angles used during the data reduction phase.

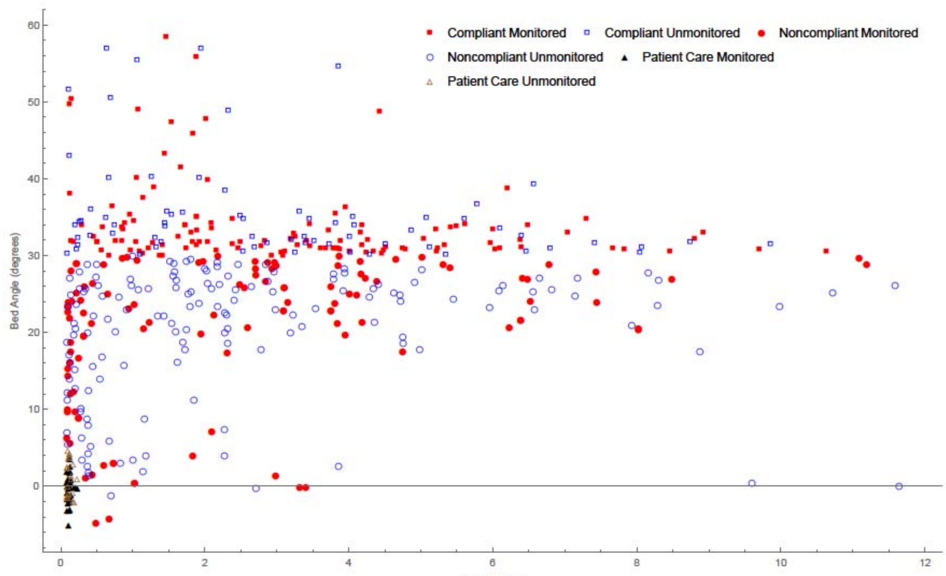

Figure 7. Head-of-bed angles of intervals of consistent bed angle plotted against the time in the interval. Intervals with a bedside monitor are indicated in red; those without a bedside monitor are in blue. The short, low-angle intervals are categorized as patient care intervals. Intervals with head-of-bed angles above 30 degrees are compliant; those below 30 degrees are noncompliant.

Taking all the intervals with durations longer than 20 minutes, an independent sample t-test indicates that the average angle of the monitored condition (M = 28.78, SD = 9.61) is larger than the average angle of the unmonitored condition (M = 25.50, SD = 10.6) ($t(383)=3.17$; $p = 0.001$). Figure 8 presents a histogram of the HOBA for each interval. The blue spike is an indication of the greater frequency of HOBAs near 30 degrees for the monitored beds.

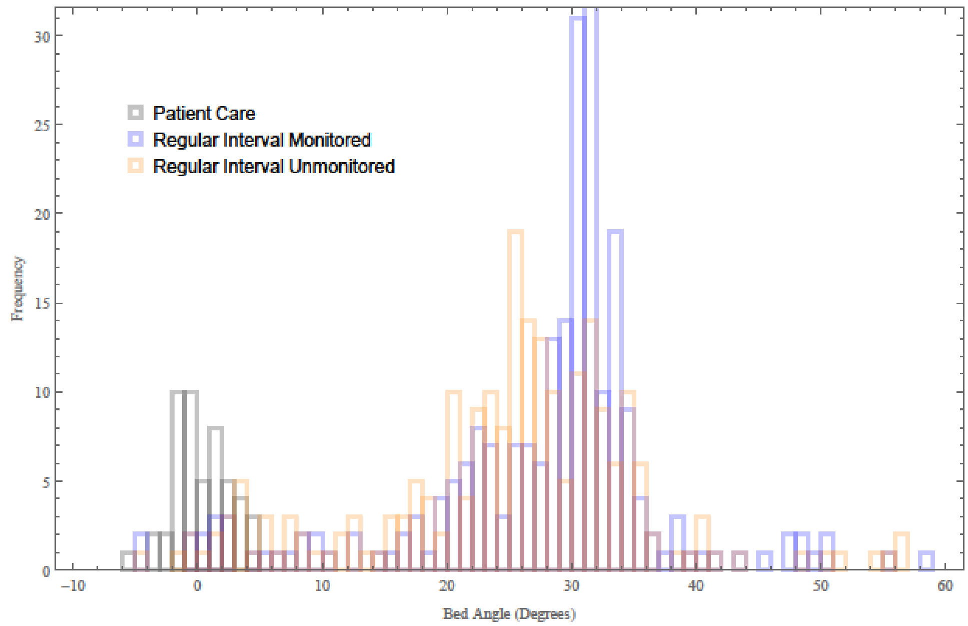

Figure 8. The histogram of interval angle indicates that the beds with bedside monitors (blue) have a peak at 30 degrees and have fewer intervals just below 30 degrees than the beds without a bedside monitor (orange). The gray peak near zero degrees represents the short, low-angle intervals assumed to be patient care intervals.

A logistic regression analysis determined that there was a significant relationship ($F(2,391)= 32.1$, $R^2=5.7\%$, $p < 0.01$) between the monitor condition, the duration of the bed-angle interval, and the compliance of the head-of-bed angles of the intervals with durations longer than 20 minutes. Of the 394 intervals, 181 were coded as compliant, because the average HOBA in these intervals was greater than or equal to 30 degrees. The binomial logistic regression was calculated using Minitab version 17.1. Predicted logit of compliance for the monitored beds = 0.1367 + 0.000015 times the bed-interval duration in seconds. Predicted logit of compliance for the unmonitored beds = -0.9163 + 0.000015 times the bed-interval duration in seconds. The probability of an unmonitored bed being in a compliant position was approximately one third the probability of a monitored bed being in a compliant angle, with a 95% confidence interval of 0.23 – 0.53.

Conclusion

The study confirms that bedside feedback improves compliance with doctor-ordered head-of-bed angles of 30 degrees. Nurse-reported HOBAs are generally not a reliable or precise measure of the actual bed angles, particularly for measuring compliance.

The data are consistent with the idea that when the nurses intend to raise the bed to the proper angle, the indicator helps them move it from a slightly below-desired position to a slightly above-desired position. It doesn't seem to change the distribution of lower bed angles or the amount of time that the bed is left in a consistent position. A histogram of the bed-angle intervals indicates a shift from bed angles just below 30 degrees to just above. Thus, it makes a substantial improvement in compliance without making a large shift in average bed angle.

Many of the other studies that used direct, bedside feedback also showed similar improvements in compliance. Using visual indicators, Bloos et al. (2009) saw compliance improvements of 22%.[36] Using audible alarms, Wolken et al. (2012) saw an increase in compliance of 15%.[24] We saw an increase of 23.2%.

Measures of the average angle are less dramatic. Rose et al. (2010) targeted 45 degrees for their intervention and found an improvement of 5 degrees,[22] which is larger than the 3.2 degrees we observed. However, the higher HOBAs they encouraged their health care workers to adopt increased the average value more than the 30 degree angles we sought. Williams, et al. (2008) saw an increase of roughly 8 degrees, compared with 3.2 degrees in our study,[21] for the longer-interval positions. Their evaluation method was daily observation rather than continuous observation, which may account for some of this difference.

To the extent that hospitals are interested in compliance, the results are clearly significant. Whether or not these small-angle differences make a clinical difference in VAP is much less clear. The Drakulovic, et al. study tracked compliance with a 45-degree standard versus zero degrees.[8] Few patients are fed at such low angles, so the original study may have been flawed. Subsequent attempts to replicate the findings have been unable to maintain the necessary bed angles, so the question remains unresolved. Given that the current bed angles do not match the source data, it is not clear that even the doctor-ordered angles are clinically efficacious, and the benefits have not been documented specifically for bed angle, only for VAP bundles.

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