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How bedside feedback improves head-of-bed angle compliance for intubated patients

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Abstract

One clinical defense against ventilator-associated pneumonia is maintaining the head-of-bed angle of ventilated patients above 30°. Most previous studies of head-of-bed angles using electronic monitoring have recorded compliance rates of less than 50%. The purpose of this study was to determine how bedside feedback of the head-of-bed angle affects bed angles set by healthcare workers. Electronic inclinometers were installed on 22 beds in an intensive care for a period of 38 days. Intubated patients were randomly assigned into two cohorts. One cohort received a graphical display of the bed angle adjacent to the in-room computer display. The head-of-bed angle of each intubated patient was continuously recorded, yielding 1,528 h of observation. The mean head-of-bed angle was 28.78° for beds with displays and 25.50° for those without, a significant difference. The most significant effects were for angles near 30°. Beds in the display cohort were three times as likely to be in a compliant position as beds in the no-display cohort. The results suggest that electronic bedside feedback improves head-of-bed angle compliance by raising angles slightly below the compliance threshold into compliance. This result may support studies of how compliant bed-angle protocols affect health outcomes.

Keywords

Protocol adherence; monitoring; head-of-bed; ventilator-associated pneumonia; wireless sensors

1. Introduction

Ventilator-associated pneumonia (VAP) is a common infection acquired in intensive care units (ICUs). In 2011, an estimated 157 000 cases of healthcare-associated pneumonia occurred in acute care hospitals in the United States (Magill *et al.*, 2014). A study of 1658 mechanically ventilated patients in 27 European ICUs found that 23.7% of the patients developed VAP (Blot *et al.*, 2011). A review of 429 research papers shows crude VAP mortality rates of 24–50%, reaching 76% for specific settings and infection by high-risk pathogens (Chastre and Fagon, 2002). Ventilated ICU patients with pneumonia have a 2- to 10-fold higher risk of death than patients without pneumonia (Eagye, Nicolau, and Kuti, 2009).

Moreover, the Centers for Disease Control and Prevention estimated that 52 543 VAP infections occur in the US each year, and that each VAP infection costs between \$14,806 and \$27,520, yielding a cost of \$0.8-\$1.4 billion (Scott, 2009). A Canadian study found that VAP accounts for approximately 17 000 ICU days per year or around 2% of all ICU days (Muscedere, Martin, and Heyland, 2008).

A standard clinical approach to preventing VAP is a set of treatments sometimes referred to as the “VAP bundle,” which typically includes an oral hygiene regimen, assessment of sedation, deep vein thrombosis prophylaxis, and maintaining bed backrest elevation between 30° and 45° (American Thoracic Society, 2006; Rotstein *et al.*, 2008). Achieving regular compliance with each aspect of this VAP bundle has been the topic of considerable research. Of particular interest to this work are the challenges associated with achieving head-of-bed angles of 30°, let alone 45° (van Nieuwenhoven *et al.*, 2006). As described in Thomas *et al.* (2015), compliance rates are particularly low when measured electronically, as opposed to compliance measures that rely on self-reports or indirect, casual or infrequent observations. This work investigates how bedside feedback may help address these low compliance rates.

2. Background

Very few studies on head-of-bed elevation have relied on consistent mechanical or electronic measurements. The few studies that used such methods tended to find the poorest compliance rates, even after focused training and process improvement. For example, Grap *et al.* (2005) electronically monitored bed angles continuously for 276 patient days and found the average angle to be 21.7°. Similarly, Markewitz *et al.* (2005) continuously monitored head-of-bed angles for 30 intubated patients over a two-month period and discovered that patients typically spent just 3% of their time at or above 30°. Bouadma *et al.* (2010) observed head-of-bed angles for 1649 ventilator days, measuring angles six times each day at random intervals. After 24 months of effort, including a series of interventions involving all healthcare workers, interventions such as developing a multidisciplinary task force, providing educational sessions, directly observing and offering performance feedback, implementing technical improvements and reminders, they were able to improve head-of-bed angle compliance rates from 5% to 58%.

Thomas *et al.* (2015) demonstrated that low compliance may be caused by the tendency of healthcare workers to inaccurately set the head-of-bed angle when adjusting the bed after patient-care activities. They found that head-of-bed angles were distributed bi-modally with one peak near 30° and a second, smaller peak near 0°. Based on observations and interviews with healthcare workers, we learned that the peak near 0° is associated with patient-care activity, such as bathing and medical procedures. During these periods, which typically last less than 20 minutes, the head-of-bed angle is lowered to facilitate the work, then re-elevated once the work has been completed. The experiment revealed no indication that healthcare workers were unaware of the desired angle, and it did not appear that they had intentionally set the head-of-bed angle lower than recommended. It seems likely, then, that non-compliance is a result of underestimating the target bed angle of 30°. If that supposition is correct, then simply providing healthcare workers with effective feedback on the bed angle should improve compliance.

Feedback of various types has a positive effect on head-of-bed angle compliance, but not all feedback is equally effective. For example, centralized feedback at the group level may help in some cases, but not uniformly. Laux *et al.* (2010) provided regular compliance feedback at weekly staff meetings and found that the frequency of compliant angles increased from three hours and six minutes each day to more than 16 hours per day. Lawrence and Fulbrook (2012) also provided centralized feedback, posting graphs in two intensive care units, but their success with head-of-bed angle compliance actually diminished in one intensive care unit, from 79.7% to 61.7% compliance, although it improved in the second intensive care unit, increasing from a compliance rate of 87.6% to 95.6%.

In contrast to group-level feedback, immediate visual feedback at the bedside, even very simple feedback, seems to be effective. Bloos *et al.* (2009) report an improvement in compliance from 24.9% to 46.9% by placing a red mark on the wall to indicate compliant positioning. Rose *et al.* (2010) use a simple dial indicator attached to the bed to make the head-of-bed angle visually prominent. During the course of the study, the average head-of-bed angle improved from 26.3° before the intervention to between 30.3 and 34.3° after the intervention. Williams *et al.* (2008) added a device that clearly indicates when the head-of-bed angle is above 30° and saw the average angle improve from 21.8° to 30.9°. Wolken *et al.* (2012) experimented with adding an audible alarm when the head-of-bed angle dropped below 28°. They found a modest improvement from 61% compliance with the display, but no audible alarm, compared to 76% compliance with the audible alarm and the bedside monitor. None of the existing studies explored the distribution of the head-of-bed angle or how feedback affected these distributions, beyond increasing the mean value. Understanding these distributions is important to creating appropriate expectations regarding the impact that further improvements might have, and for targeting specific head-of-bed angle patterns.

We hypothesized that immediate bedside feedback would help healthcare workers be more accurate in achieving the target bed angle. Consequently, we expected to see that the availability of immediate, visual head-of-bed angle feedback would cause healthcare workers to more frequently set the head-of-bed angle to a position at or above 30°. We also expected that the compliance gains would come mostly from a shift of measurements just below 30° to just above 30°.

3. Methods

The experiment was conducted in the intensive care unit of a large, Midwestern hospital. Electronic bed-angle sensors (Fig. 1) were placed on all 22 beds in four of the five work areas in the intensive care unit. The four work areas were selected because they were most likely to host intubated patients. Each work area consisted of five or 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 bedside bed-angle display would be placed in the room. The bedside display was mounted above the in-room computer that nurses generally use to enter patient data while performing patient-care activities. The

display received the bed-angle broadcast from the bed-angle sensor and displayed the head-of-bed angle (Fig. 2). The display was color-coded: green when above 30° and red when below 30°. The bedside display remained in the room and operative until it was removed when the patient was extubated.

The local Institutional Review Board and the Nursing Research and Evidence-Based Practice Committee approved the experimental protocol.

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 supplemented with e-mail. Near the middle of the experiment, the bed-angle sensors were each removed for several hours in order to recharge batteries. Also during the experiment, a staff physician kept a record of when each patient in the study was intubated or removed from intubation as well as a record of the ordered head-of-bed angle and the head-of-bed angles recorded in the patient's electronic chart by the nurses.

The bed-angle sensors were purpose-built for this study. They include an inclinometer, memory, microprocessor and radio. A bubble-level enables the device to be mounted on the steel bedframe when the bed is in the horizontal position. Periodically, and when the bed angle is changed, the sensor both stores and transmits the bed angle.

The bedside display used an Android application running on a Nexus 7 tablet. The tablet received radio transmissions from the bed sensor through a radio connected to its serial port, and both stored and displayed the transmitted bed angle. The tablet was mounted above the in-room computer with an adjustable mount designed to mount tablets to wheelchairs. The nurses often interacted with the in-room computer, checking the patient record and recording information about patient care activities; for example, before and after performing these tasks.

4. Results

During the study, 28 intubated patients were observed. Five of these records proved unreliable and, therefore, were discarded from the analysis. Reasons included: software failures (1), electrical failures (3), or mechanical failures (1). Of the remaining 23 patients, 11 were monitored and 12 were unmonitored. The doctor-ordered head-of-bed angle for each of these intubated patients was 30°, and individual patients were observed for periods ranging from 12 hours to 38 days.

Nurses recorded 605 head-of-bed angle entries in the study patients' electronic medical records. A total of 533 of these reports (88%) documented head-of-bed angles of 30°, 8 reports (1%) documented angles less than 30°, and 64 reports (11%) documented angles greater than 30°.

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

Figure 3 presents a representative sample of the electronic record for two patients. The continuous electronic record of bed angles was divided into intervals with a relatively stable bed angle, using the approach presented in Thomas *et al.* (2015). Stable bed-angle intervals generally occurred between periods of rapid bed-angle change when, for example, a nurse adjusted the bed angle during normal patient care activities. Occasionally, the bed was lowered to a position lower than horizontal so that the head-of-bed was at a negative angle. The analysis revealed 512 intervals with a stable bed angle, including 267 intervals with the display cohort and 245 with the no-display cohort. The stable bed-angle intervals were used as the basis of analysis because each stable interval represents a decision by a healthcare worker to set the bed at a particular angle, and thus constitutes a natural element of analysis. The intervals spanned 812.5 h of observation for the display cohort and 715.6 for the no-display cohort. The duration of the intervals ranged from 0.08 to 69.1 h, with an average interval length of 2.99 h and a standard deviation of 5.08 h. A Mann-Whitney test indicated that the median duration of the display intervals (2.0 h) was not significantly different from the non-display intervals (1.7 h), $W = 69319$, $p = 0.62$.

A Mann-Whitney test indicated that the median head-of-bed angle from the display (29.4°) cohort was significantly larger than the non-display cohort (25.6°), $p = 0.0048$. Wilcoxon signed-rank tests indicate that the median head-of-bed angle for both cohorts was significantly less than the target of 30° (display: $p < 0.001$; non-display: $p < 0.001$). However, if intervals with durations of less than 20 min are neglected, periods which are often the result of patient care activities, the median head-of-bed angle for the 200 long-duration intervals in the display cohort is not significantly different from the target of 30° ($p = 0.688$). The median of the 192 long-duration intervals in the non-display cohort is still significantly smaller than 30° ($p < 0.001$).

Considering all intervals, the head-of-bed angle was compliant, meaning greater than or equal to 30° , in 124 of the 267 display-cohort intervals (46%), but only 72 of 245 in the non-display cohort intervals (29%), a significant difference ($Z = 4.04$, $p < 0.001$). This pattern is even more pronounced when considering intervals longer than 20 minutes, in which the display cohort had a compliance rate of 58% versus 33% for the non-display cohort, also a significant difference ($Z = 5.28$, $p < 0.001$).

Figure 4 presents a histogram of the head-of-bed angle for all intervals. The light bars indicate the frequency of monitored intervals, the medium-gray bars the frequency of unmonitored intervals, and the darkest regions indicate overlap between both bars. Figure 5 presents the stable bed angles versus the length of the interval in hours. The squares indicate the duration and angle of unmonitored intervals, and the circles indicate the duration and angle of the monitored intervals.

The head-of-bed angles were further analyzed by considering the angle error, the value of the difference between the interval angle, and the acceptable range of 30 – 45° specified by the CDC (Tablan *et al.*, 2003). Angles greater than 45° were assigned a positive error value and angles less than 30° were assigned a negative error value. The angles were modeled with the following equation:

$$\alpha_{ij} = \mu + c + p_i(c) + \varepsilon_j$$

where α_{ij} is the head-of-bed angle error during interval j for patient i , under experimental condition c (monitored or unmonitored), treating patient as a random variable, and ε_j is normally distributed, random error. The data were fit to this model, weighing each interval by its duration, using a general linear model in Minitab 17. Table 1 displays the resulting analysis of variance for the model, which had an adjusted R-square of 34.48%.

5. Discussion

The study confirms that immediate bedside feedback regarding the head-of-bed angle improves compliance with doctor-ordered head-of-bed angles of 30°. It also reiterates previous findings that nurse-reported head-of-bed angles are generally not a reliable or precise measure of the actual bed angles, particularly for measuring compliance. While 98.7% of the nurse-reported head-of-bed angles were compliant in the electronic medical record, only 38% percent were compliant when measured electronically. The consistency of the 30° value in the patients' electronic medical records seems to indicate a nominal value rather than a direct observation, particularly in light of the angle variation observed by our angle sensors.

The data in Fig. 4 suggest that immediate feedback tends to generally influence healthcare workers to raise the head-of-bed from positions between 25° and 30° to compliant positions between 30° and 35°. Feedback does not appear to greatly change the distribution of other bed angles, nor, as Fig. 5 indicates, does feedback appear to greatly affect the amount of time the bed is left in a consistent position. Thus, immediate feedback 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 showed compliance improvements similar to what we observed. Using visual indicators, Bloos *et al.* (2009) saw compliance improvements of 22%. Using audible alarms, Wolken *et al.* (2012) saw a compliance increase of 15%. Rose *et al.* (2010) found compliance improved from 32.1% to 70.4% at the end of their study for the 30° angle criterion. Williams *et al.* (2008) measured compliance of 22.9% without feedback and 71.6% with feedback. These values are somewhat smaller than the compliance improvements we observed across our full dataset, but similar to our long-interval observations of 58% compliance without feedback and 33% compliance with feedback, an increase of 25%.

Measures of the average angle are less dramatic. Rose *et al.* (2010) saw a sustained, long-term improvement of 5°, after providing feedback and training, though initially they saw gains as high as 9°. Rose *et al.* (2010) targeted 45° for their intervention. Although they failed to achieve this high target, it may have helped to increase their average response. Williams *et al.* (2008) measured an increase of 9°, from 22° to 31°, compared to an increase of 3.3° in the long intervals observed in this study. The Williams *et al.* study measured bed elevation with daily observation, ignoring observations taken during patient care activities, which may account for some of this difference.

To the extent that hospitals are interested in compliance, the results of this study are clearly significant; feedback improved compliance. Whether or not these small angle differences make a clinical difference in VAP is much less clear. The Drakulovic *et al.* study compared 45° and 0° head-of-bed angles. Few patients are fed intravenously when the head of bed is positioned 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 even clear that doctor-ordered angles are clinically efficacious, and the benefits have not been documented specifically for bed angle, only for VAP bundles.

This research suffers from several limitations. The presence of the displays on some beds may serve as a compliance reminder to other nurses, particularly for any nurse working with two intubated patients, one with a display and one without. It is also important to note that the beds already have a small, mechanical inclinometer to indicate the head-of-bed angle, so the feedback is redundant; the feedback provided in this experiment was simply more precise and more salient than the existing feedback. The ICU in this study was used in three head-of-bed angle studies, although the experiments were widely spaced. The unit has a high baseline compliance rate and is often involved in improvement projects, so it may not be representative of other units. Finally, the data reduction algorithm does not account for 100% of the bed angles because it focuses on stable intervals. A standard for analyzing bed angles has not yet been proposed, although such a standard could provide a more nuanced definition of head-of-bed angle compliance.

Such a definition of compliance is surely necessary, since the current definition does not allow for patient care activities. It seems reasonable that clinicians should adopt a framework with more flexibility if continuous monitoring is used, such as ordering that the head-of-bed angle be positioned to at least 30 degrees 80% of the time. Perhaps the average angle could be used, although this could lead to nurses setting higher bed angles in order to make up for periods of patient care activities, potentially an undesirable behavior. With a more standardized measurement approach, it may become easier to compare feedback techniques to improve compliance and, ultimately, to test the efficacy of head-of-bed angles on patient outcomes.

6. Conclusions

This single-unit study explores how immediate, electronic feedback affected the head-of-bed angles of intubated patients in an ICU. The study included 715.6 h without a bedside display and 812.5 h with a bedside display. The prominent display of the bed angle significantly improved compliance with the doctor-ordered 30° head-of-bed angle criterion. Most of the gain was achieved in a shift of stable head-of-bed angles from just below 30° to just above 30°. Although compliance rates improved, it is less clear that the 3.8° improvement in the median angle has clinical importance, as few studies on the effect of head-of-bed angle on ventilator-associated pneumonia have been possible because of the difficulties of maintaining head-of-bed angle compliance.

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References

- American Thoracic Society. (2006) Guidelines for the management of adults with hospital-acquired, ventilator-associated, and healthcare-associated pneumonia. *American Journal of Respiratory and Critical Care Medicine*, 171, 388–416.
- Balonov K, Miller AD, Lisbon A, and Kaynar AM (2007) A novel method of continuous measurement of head of bed elevation in ventilated patients. *Intensive Care Medicine*, 33(6), 1050–1054. [PubMed: 17393138]
- Berenholtz SM, Pham JC, Thompson DA, Needham DM, Lubomski LH, Hyzy RC, Welsh R, et al. (2011) Collaborative cohort study of an intervention to reduce ventilator-associated pneumonia in the intensive care unit. *Infection Control and Hospital Epidemiology*, 32(4), 305–314. [PubMed: 21460481]
- Bingham M, Ashley J, De Jong M, and Swift C (2010) Implementing a unit-level intervention to reduce the probability of ventilator-associated pneumonia. *Nursing Research*, 59(1 Suppl), S40–S47. [PubMed: 20010277]
- Bion JF, Abrusci T, and Hibbert P (2010) Human factors in the management of the critically ill patient. *British Journal of Anaesthesia*, 105(1), 26–33. [PubMed: 20511333]
- Bird D, Zambuto A, O'Donnell C, Silva J, Korn C, Burke R, et al. (2010) Adherence to ventilator-associated pneumonia bundle and incidence of ventilator-associated pneumonia in the surgical intensive care unit. *Archives of Surgery*, 145(5), 465–470. [PubMed: 20479345]
- Bloos F, Müller S, Harz A, Gugel M, Geil D, Egerland K, et al. (2009) Effects of staff training on the care of mechanically ventilated patients: A prospective cohort study. *British Journal of Anaesthesia*, 103(2), 232–237.
- Blot SI, Serra ML, Koulenti D, Lisboa T, Deja M, Myrianthefts P, et al. (2011) Patient to nurse ratio and risk of ventilator-associated pneumonia in critically ill patients. *American Journal of Critical Care*, 20(1), e1–e9. [PubMed: 21196562]
- Bouadma L, Mourvillier B, Deiler V, Le Corre B, Lolom I, Régnier B, et al. (2010) A multifaceted program to prevent ventilator-associated pneumonia: Impact on compliance with preventive measures. *Critical Care Medicine*, 38(3), 789–796. [PubMed: 20068461]
- Cason CL, Tyner T, Saunders S, and Broome L (2007) Nurses' implementation of guidelines for ventilator-associated pneumonia from the Centers for Disease Control and Prevention. *American Journal of Critical Care*, 16(1), 28–37. [PubMed: 17192524]
- Chastre J, and Fagon JY (2002) Ventilator-associated pneumonia. *American Journal of Respiratory and Critical Care Medicine*, 165(7), 867–903. [PubMed: 11934711]
- Drakulovic MB, Torres A, Bauer TT, Nicolas JM, Nogue S, and Ferrer M (1999) Supine body position as a risk factor for nosocomial pneumonia in mechanically ventilated patients: A randomised trial. *The Lancet*, 354(9193), 1851–1858.
- Dubose J, Teixeira PGR, Inaba K, Lam L, Talving P, Putty B, Plurad D, et al. (2010) Measurable outcomes of quality improvement using a daily quality rounds checklist: One-year analysis in a trauma intensive care unit with sustained ventilator-associated pneumonia reduction. *Journal of Trauma and Acute Care Surgery*, 69(4), 855–860.
- Dudeck MA, Weiner LM, Allen-Bridson K, et al. (2013) National Healthcare Safety Network (NHSN) report, data summary for 2012, "Device-Associated Module." *American Journal of Infection Control*, 41(12), 1148–66. [PubMed: 24274911]
- Eagye KJ, Nicolau DP, and Kuti JL (2009) Impact of superinfection on hospital length of stay and costs in patients with ventilator-associated pneumonia. *Seminars in Respiratory and Critical Care Medicine*, 30(1), 116–123. [PubMed: 19199193]

- Efrati S, Deutsch I, Antonelli M, Hockey PM, Rozenblum R, and Gurman GM (2010) Ventilator-associated pneumonia: Current status and future recommendations. *Journal of Clinical Monitoring and Computing*, 24(2), 161–168. [PubMed: 20237830]
- El-Khatib MF, Zeineldine S, Ayoub C, Husari A, and Bou-Khalil PK (2010) Critical care clinicians' knowledge of evidence-based guidelines for preventing ventilator-associated pneumonia. *American Journal of Critical Care*, 19(3), 272–276. [PubMed: 19687515]
- Fries J, Hlady C, Herman T, Polgreen PM, and Segre AM (2012) A low-cost non-RFID based method for automated monitoring of hand hygiene compliance. Program and Abstracts of the 19th Annual Scientific Meeting of the Society for Healthcare Epidemiology of America (SHEA), San Diego, CA Abstract 123.
- Fries J, Segre AM, Thomas GW, Herman T, Ellingson K, and Polgreen PM (2012) Monitoring hand hygiene via human observers: How should we be sampling? *Infection Control and Hospital Epidemiology*, 33(7), 689–695. [PubMed: 22669230]
- Grap MJ, Munro CL, Hummel RS, Elswick RK, McKinney JL, and Sessler CN (2005) Effect of backrest elevation on the development of ventilator-associated pneumonia. *American Journal of Critical Care*, 14(4), 325–332. [PubMed: 15980424]
- Grimshaw JM, Shirran L, Thomas R, Mowatt G, Fraser C, Bero L, Grilli R, Harvey E, Oxman A, and O'Brien MA (2001) Changing provider behavior: An overview of systematic reviews of interventions. *Medical Care*, 39(8 Suppl 2), II2–II45. [PubMed: 11583120]
- Hawe CS, Ellis KS, Cairns CJ, and Longmate A (2009) Reduction of ventilator-associated pneumonia: Active versus passive guideline implementation. *Intensive Care Medicine*, 35(7), 1180–1186. [PubMed: 19308354]
- Helman DL Jr., Sherner JH III, Fitzpatrick TM, Callender ME, and Shorr AF (2003) Effect of standardized orders and provider education on head-of-bed positioning in mechanically ventilated patients. *Critical Care Medicine*, 31(9), 2285–2290. [PubMed: 14501958]
- Herman T, Pemmaraju SV, Segre AM, Polgreen PM, Curtis DE, Fries J, et al. (2009) Wireless applications for hospital epidemiology. Proceedings of the 1st ACM International Workshop on Medical-Grade Wireless Networks, New Orleans, LA, 45–50.
- Hornbeck T, Curtis DE, Herman T, Thomas G, Segre AM, and Polgreen PM (2011) Contact patterns for HCWs: Not everyone is the “average.” 21st Annual Scientific Meeting of the Society for Healthcare Epidemiology of America, Dallas, TX Abstract 423.
- Hornbeck T, Naylor D, Segre AM, Thomas G, Herman T, and Polgreen PM (2012) Using sensor networks to study the effect of peripatetic healthcare workers on the spread of hospital-associated infections. *Journal of Infectious Diseases*, 206(10), 1549–1557. [PubMed: 23045621]
- Hysong SJ (2009) Meta-analysis: Audit and feedback features impact effectiveness on care quality. *Medical Care*, 47(3), 356–363. [PubMed: 19194332]
- Hysong SJ, Best RG, and Pugh JA (2006) Audit and feedback and clinical practice guideline adherence: Making feedback actionable. *Implementation Science*, 1(1), 9. [PubMed: 16722539]
- Kaynar AM, Mathew JJ, Hudlin MM, Gingras DJ, Ritz RH, Jackson MR, et al. (2007) Attitudes of respiratory therapists and nurses about measures to prevent ventilator-associated pneumonia: A multicenter, cross-sectional survey study. *Respiratory Care*, 52(12), 1687–1694.
- Kluger AN, and DeNisi A (1998) Feedback interventions: Toward the understanding of a double-edged sword. *Current Directions in Psychological Science*, 7(3), 67–72.
- Labeau S, Vandijck DM, Claes B, Van Aken P, Blot SI, and on behalf of the executive board of the Flemish Society for Critical Care Nurses. (2007) Critical care nurses' knowledge of evidence-based guidelines for preventing ventilator-associated pneumonia: An evaluation questionnaire. *American Journal of Critical Care*, 16(4), 371–377. [PubMed: 17595369]
- Laux L, Dysert K, Kiely S, and Weimerskirch J (2010) Trauma VAP SWAT team: A rapid response to infection prevention. *Critical Care Nursing Quarterly*, 33(2), 126–131. [PubMed: 20234201]
- Lawrence P, and Fulbrook P (2012) Effect of feedback on ventilator care bundle compliance: Before and after study. *Nursing in Critical Care*, 17(6), 293–301. [PubMed: 23061619]
- Leape LL (1994) Error in medicine. *JAMA: The Journal of the American Medical Association*, 272(23), 1851–1857. [PubMed: 7503827]

- Leape LL, and Berwick DM (2005) Five years after to err is human. *JAMA: The Journal of the American Medical Association*, 293(19), 2384–2390. [PubMed: 15900009]
- Magill SS, Edwards JR, Bamberg W, et al. (2014) Multistate point- prevalence survey of health care-associated infections. *New England Journal of Medicine*, 370(13), 1198–208. [PubMed: 24670166]
- Markewitz BA, Mayer J, Westenskow D, and Richardson S (2005) Use of an inclinometer-data logger tool for continuous recording of head of bed position in patients undergoing mechanical ventilation. *CHEST Journal*, 128(4_MeetingAbstracts), 303S–b.
- Marra AR, Cal RGR, Silva CV, Caserta RA, Paes AT, Moura DF Jr., et al. (2009) Successful prevention of ventilator-associated pneumonia in an intensive care setting. *American Journal of Infection Control*, 37(8), 619–625. [PubMed: 19559503]
- Moteiv Corporation. (2004) Telos Rev B (Low Power Wireless Sensor Module) Preliminary Datasheet. <http://www2.ece.ohio-state.edu/~bibyk/ee582/telosMote.pdf>.
- Muscudere JG, Martin CM, and Heyland DK (2008) The impact of ventilator-associated pneumonia on the Canadian health care system. *Journal of Critical Care*, 23(1), 5–10. [PubMed: 18359415]
- Peterlini MAS, Rocha PK, Kusahara DM, and Pedreira ML (2006) Subjective assessment of backrest elevation: Magnitude of error. *Heart & Lung: The Journal of Acute and Critical Care*, 35(6), 391–396. [PubMed: 17137940]
- Polgreen PM, Hlady CS, Severson MA, Segre AM, and Herman T (2010) Method for automated monitoring of hand hygiene adherence without radio-frequency identification. *Infection Control and Hospital Epidemiology: The Official Journal of the Society of Hospital Epidemiologists of America*, 31(12), 1294.
- Reason J (2000) Human error: Models and management. *British Medical Journal*, 320(7237), 768–770. [PubMed: 10720363]
- Reason J (2005) Safety in the operating theatre: Part 2: Human error and organisational failure. *Quality & Safety in Health Care*, 14(1), 56–60. [PubMed: 15692005]
- Reid PP, Compton WD, Grossman JH, and Fanjiang G (Eds.). (2005) *Building a Better Delivery System: A New Engineering/Health Care Partnership*. National Academies Press, Washington, DC.
- Rose L, Baldwin I, and Crawford T (2010) The use of bed-dials to maintain recumbent positioning for critically ill mechanically ventilated patients (The RECUMBENT study): Multicentre before and after observational study. *International Journal of Nursing Studies*, 47(11), 1425–1431. [PubMed: 20471649]
- Rotstein C, Evans G, Born A, Grossman R, Light RB, Magder S, et al. (2008) Clinical practice guidelines for hospital-acquired pneumonia and ventilator-associated pneumonia in adults. *The Canadian Journal of Infectious Diseases & Medical Microbiology*, 19(1), 19–53. [PubMed: 19145262]
- Scott RD (2009) The direct medical costs of healthcare-associated infections in US hospitals and the benefits of prevention. National Center for Preparedness, Detection, and Control of Infectious Diseases (U.S.), Division of Healthcare Quality Promotion, 1–16.
- Sexton JB, Thomas EJ, and Helmreich RL (2000) Error, stress, and teamwork in medicine and aviation: Cross-sectional surveys. *British Medical Journal*, 320(7237), 745–749. [PubMed: 10720356]
- Tablan OC, Anderson LJ, Arden NH, Breiman RE, Butler JC, and McNeil MM (1994) Guideline for prevention of nosocomial pneumonia. *Infection Control and Hospital Epidemiology*, 15(9), 587–627. [PubMed: 7989733]
- Tablan OC, Anderson LJ, Besser R, Bridges C, and Hajjeh R (2003) CDC: Healthcare Infection Control Practices Advisory Committee: Guidelines for preventing health-care-associated pneumonia, 2003: Recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee. *MMWR Recomm Rep*, 53(RR-3), 1–36.
- Thomas GW, Pennathur P, Falk DM, Myers J, Ayres B, and Polgreen PM (2015) How lapse and slip errors influence head-of-bed angle compliance rates as measured by a portable, wireless data collection system. *IIE Transactions on Healthcare Systems Engineering*, 5(1), 1–13. [PubMed: 31168335]

- US Department of Health and Human Services. (2012) Healthcare- associated infection (HAI) <http://www.hhs.gov/ash/initiatives/hai/index.html>.
- Valdez RS, Ramly E, and Brennan PF (2010) Final Report: Industrial and Systems Engineering and Health Care: Critical Areas of Research. AHRQ Publication 10–0079. Agency for Healthcare Research and Quality, Rockville, MD.
- van Nieuwenhoven CA, Vandenbroucke-Grauls C, van Tiel FH, Joore HC, van Schijndel RJS, van der Tweel I, et al. (2006) Feasibility and effects of the semirecumbent position to prevent ventilator-associated pneumonia: A randomized study. *Critical Care Medicine*, 34(2), 396402.
- Williams Z, Chan R, and Kelly E (2008) A simple device to increase rates of compliance in maintaining 30-degree head-of-bed elevation in ventilated patients. *Critical Care Medicine*, 36(4), 1155–1157. [PubMed: 18379241]
- Wolken RF, Woodruff RJ, Smith J, Albert RK, and Douglas IS (2012) Observational study of head of bed elevation adherence using a continuous monitoring system in a medical intensive care unit. *Respiratory Care*, 57(4), 537–543. [PubMed: 22005904]
- Zapf D, and Reason JT (1994) Introduction: Human errors and error handling. *Applied Psychology*, 43(4), 427–432.
- Zaydfudim V, Dossett LA, Starmer JM, Arbogast PG, Feurer ID, Ray WA, et al. (2009) Implementation of a real-time compliance dashboard to help reduce SICU ventilator-associated pneumonia with the ventilator bundle. *Archives of Surgery*, 144(7), 656–662. [PubMed: 19620546]

Figure 1.

Left, a prototype of the bed angle monitor with bubble level indicator, USB port, and LED indicators. Right, the inside of the device revealing two circuit boards, a rechargeable battery and the magnet on the back cover.

Figure 2. Bedside display. The display was placed directly above the in-room computer monitor. The number at top indicates the current head-of-bed angle.

Figure 3.

Typical samples of the electronic record showing the head-of-bed angles for two intubated patents, one with and one without a feedback display. The broad, semi-transparent horizontal bars indicate the intervals used to summarize the stable angle regions for analysis.

Figure 4.
A categorized histogram of the stable monitored and unmonitored bed angles.

Figures 5.

A plot of the duration of each stable bed interval and the angle of the stable bed interval. The horizontal line indicates the compliance threshold of 30 degrees.

Table 1.

Analysis of variance for the bed tilt model.

Source	DF	Adj SS'	Adj MS	F-Value	P-Value
Condition	1	11929175	11929175	5.23	0.031
Patient (Condition)	21	95278737	4537083	11.86	0.000
Error	489	187120102	382659		
Total	511	298457550			

* Note that the p -value for condition is not an exact t-test.