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Automated Near Real-Time Ventilator Data Feedback Reduces Incidence of Ventilator-Associated Events: A Retrospective Observational Study

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OBJECTIVES: Critical care teams are encouraged to follow best practice protocols to help wean mechanically ventilated patients from the ventilator to reduce ventilator-associated events including ventilator-associated conditions, probable ventilator-associated pneumonias, and infection-related ventilator-associated conditions. Providers monitor for alerts suggestive of possible ventilator-associated events and advise when patients should undergo spontaneous breathing trials. Compliance with protocols in most units is suboptimal.

DESIGN: Retrospective review of clinical data over 24 months.

SETTING: St. Joseph Mercy Hospital Candler Hospital Medical-Surgical ICU.

PATIENTS: All mechanically ventilated patients.

INTERVENTIONS: The Respiratory Knowledge Portal was implemented in our ICU. For 13 months, Respiratory Knowledge Portal data were ported to ICU workstations (control). For the following 11 months, Respiratory Knowledge Portal data were also presented on tablet computers (intervention) for use during multidisciplinary rounds. We performed a retrospective review of Respiratory Knowledge Portal data from before and after the implementation of the tablet computers.

MEASUREMENTS AND MAIN RESULTS: Data were collected from 337 patients (187 control group, 150 intervention group). A decrease in the occurrence of ventilator-associated events was observed during the intervention group compared with the control group. Only 2.0% of patients in the intervention group experienced any category of ventilator-associated event, while 11.2% of patients in the control group experienced one event ($p = 0.003$). Intervention patients experienced less ventilator-associated conditions ($p = 0.002$), infection-related ventilator-associated conditions ($p = 0.026$), and probable ventilator-associated pneumonias ($p = 0.036$) than control patients. Twenty-one of the 24 patients with any ventilator-associated events were in the control group. There was no significant difference between the days spent on ventilation nor hospital length of stay in the control compared with intervention group patients.

CONCLUSIONS: Fewer ventilator-associated events, ventilator-associated conditions, infection-related ventilator-associated conditions, and probable ventilator-associated pneumonias were seen during the period when Respiratory Knowledge Portal monitoring data was presented on tablet computers. There was no difference in time on ventilator nor overall length of stay.

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KEY WORDS: length of stay; mechanical ventilation; spontaneous breathing trial; ventilator-associated event; ventilator-associated pneumonia; weaning

The care of the mechanically ventilated patient requires a comprehensive approach focusing on treating disease processes, maintaining cardiopulmonary homeostasis, supporting patient-induced recovery, and avoiding complications that arise from the care itself. This is no small task and necessitates high-level organization of multiple subspecialty medical teams, laboratory and pathology data, and ever-changing requirements from physiologic support equipment (e.g., ventilators). Gathering real-time or trended information and recommendations from multiple sources as it pertains to an individual patient remains challenging in the workplace where humans are required to efficiently locate, keep up with, and organize data in such a way that is useful to guide further care and identify patient deterioration early.

Of utmost importance during mechanical ventilation is the prevention of adverse events that may occur during its use. Ventilator-associated events (VAEs), as defined by the Centers for Disease Control and Prevention (CDC) to include ventilator-associated conditions (VACs), infection-related ventilator-associated conditions (IVACs), and probable ventilator-associated pneumonias (PVAPs), increase morbidity/mortality in patients and increase costs to both patients and healthcare facilities (1, 2). Avoidance of such complications is paramount to providing high-level care.

Guidelines and best practice protocols have been described in the literature to assist clinicians in identifying key information and suggest treatment regimens that are proven effective in weaning from mechanical ventilation and minimizing VAEs (3–6). Protocol compliance, specifically compliance with spontaneous breathing trials (SBTs), has been associated with rapid liberation from the ventilator, reductions in VAEs, and reductions in healthcare costs. More importantly, timely successful weaning has been shown to save lives (4, 5, 7–9). Despite having weaning protocols in place, patient outcomes in the real-world setting often do not reflect those in prospective studies, likely because of how difficult it is outside of a clinical trial to compile and organize the data and numerous medical teams required to practice them efficiently (8).

The Respiratory Knowledge Portal (RKP) (Vyaire Medical, Mettawa, IL) is an electronic system that gathers crucial physiologic and nonphysiologic information on mechanically ventilated patients and presents it across multiple medical teams to assist in their clinical management and recognition of adverse events. RKP can be individualized according to an institution's best weaning practice protocols for mechanical ventilation and historically was outputted to a central workstation for review by medical teams, showing both patient data and adherence to the institution's protocols (9).

Using RKP, patient trends, including improvement and deterioration, are easily visualized to guide clinician management. However, its centralized access point makes it potentially challenging to incorporate into real-time care at the bedside among disparate medical teams. Implementation of a remote RKP via a tablet interface may allow this near real-time information to be better used in a clinical setting to improve patient care and reduce VAEs. At our institution, where RKP at the central workstation has been present, we hypothesized that introduction of the tablet version of RKP would reduce the incidence of VAEs, decreasing potentially avoidable patient complications.

We conducted a retrospective observational study evaluating the incidence of VAEs in mechanical ventilation patients before and after the implementation of a tablet-based RKP.

MATERIALS AND METHODS

Setting and Subjects

We collected data for all mechanically ventilated patients in the St. Joseph Mercy Hospital Candler Hospital Medical-Surgical ICU between January 15, 2014, and December 30, 2015. Inclusion criteria for the study were all mechanically ventilated patients above the age of 18 years old and who were mechanically ventilated for at least 3 days. The study received Institutional Review Board approval and is registered by St. Joseph's/Candler Health System on ClinicalTrials.gov (NCT03850340). Given the retrospective and anonymized nature of the study, signed informed consent was not required.

Intervention

In the initial 13 months of the study, the RKP system was loaded with the institution's best practice protocols

for weaning including indicators for SBTs and for extubation. During this time, clinical staff used the workstation computer version of RKP. On February 9, 2015, RKP data was ported to tablet computers that were used during daily rounds by ICU staff, primarily respiratory therapists. Patients were divided into two groups, based on whether they were ventilated before tablets were implemented (controls) or after (intervention). For patients that started on the ventilator during the control period and continued into the intervention period, the total time spent on the ventilator during each period was quantified and patients were categorized in the group in which they spent more time.

Study Data

The following data were collected for each patient: age, sex, primary diagnosis, comorbidities, outcome, hospital admission and discharge date and time, and ventilator start and termination date and time. VAEs were automatically identified and recorded by the RKP software according to the CDC definitions (1). Using the CDC definitions, VACs, IVACs, and PVAPs were identified for each patient.

Data and Statistical Analysis

The incidence of VAEs was quantified as the number of patients in each group who had each category of event divided by the total number of patients in that group. Ventilator duration was defined as the number of days between ventilator start and termination, and hospital length of stay was defined as the number of days between hospital admission and discharge. For patients who experienced at least one VAE, we identified the number of days between ventilation start and the occurrence of the first VAE. Estimated costs based on changes in VAE incidence were estimated at $40,144 per VAE avoided based on previous research (10).

An unpaired *t* test was used to compare patient ages between the control and intervention groups, and Fisher exact test was used to compare the proportion of males to females in the two groups. Fisher exact tests compared the incidence of VACs, IVACs, and PVAPs between the control and intervention groups. Incidence of a patient experiencing any VAE during the control and intervention periods was also compared using a Fisher exact test. Wilcoxon rank-sum tests compared the median ventilation duration and hospital length of stay of the patients in the control and intervention groups as well as between patients that did and did not experience a VAE. All analyses were performed using MATLAB (MathWorks, Natick, MA).

Sample Size Justification

Sample size for this study was calculated based on the ability to show a difference in VAE incidence between the control and intervention periods. We assumed a 10% VAE incidence in the control group and 3% VAE incidence in the intervention group, which corresponds to an effect size of 28%. Based on the sample size formula for two independent samples with dichotomous outputs, at least 260 total patients (130 in each group) were necessary to show a significant difference in VAE incidence between the groups with 90% power and 5% significance level.

RESULTS

Data were collected from a total of 337 patients, of which 187 were in the control group and 150 in the intervention group. Eight patients were initially managed without tablets before being switched over to tablet-based management. Of those eight, three were classified as controls while five were classified as intervention based on the number of days of treatment with each system. None of these eight patients experienced a VAE. Patients in the intervention group were slightly older (mean age 66.5, SD 13.9 yr vs 62.8, SD 13.5 yr; $p = 0.015$) and had similar proportions of males and females (controls 46.2% male, intervention 50% male; $p = 0.154$).

A decrease in the incidence of VAEs was observed during the intervention period compared with the control period (**Table 1** and **Fig. 1**). Specifically, only 2.0% of patients in the intervention group experienced any category of VAE, while 11.2% of patients in the control group experienced one event ($p = 0.003$). Intervention patients experienced less VACs ($p = 0.002$), IVACs ($p = 0.026$), and PVAPs ($p = 0.036$) than control patients. A reduction in VAE incidence from 11.2% to 2.0% translates to an average savings of nearly $3,700 per patient ([11.2–2.0%] × $40,144).

A total of 24 patients (7%) experienced at least one VAE during their hospital stay, while 313 patients (93%) did not experience a VAE. Twenty-one of the 24 patients with any VAEs were in the control group.

TABLE 1.
Incidence of Ventilator-Associated Events for the Control and Intervention Groups

VAE Classification	Control	Intervention	*p*
Ventilator-associated condition	9.1	1.3	0.002
Infection-related ventilator-associated condition	5.3	0.7	0.026
Probable ventilator-associated pneumonia	3.2	0.0	0.036
Any VAE	11.2	2.0	0.003

VAE = ventilator-associated event.
VAEs were categorized into three categories, as defined by the Centers for Disease Control and Prevention: ventilator-associated condition, infection-related ventilator-associated conditions, and probable ventilator-associated pneumonias. Incidences were compared using Fisher exact test.

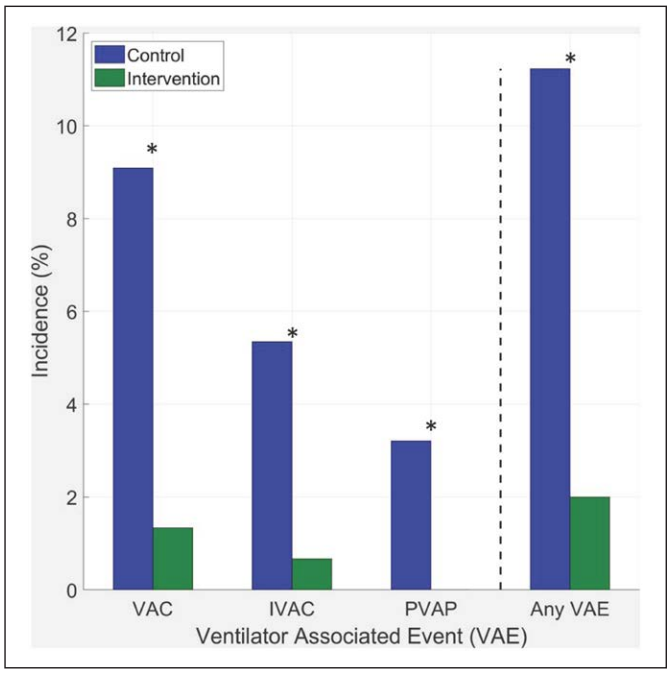

Figure 1. Incidence of ventilator-associated events (VAEs) in the control (*blue*) and intervention (*green*) groups. VAEs were categorized as: ventilator-associated condition (VAC), infection-related ventilator-associated conditions (IVAC), and probable ventilator-associated pneumonias (PVAPs). The intervention group had significantly lower incidences of VAC, IVAC, PVAP, and total VAEs compared with the control group (*$p < 0.05$).

Patients who experienced at least one VAE during their hospital stay had median ventilator durations that were more than 2.5 times longer than patients that did not have a VAE (18 vs 7 d; $p < 0.0001$) (**Table 2**). Patients with a VAE also had median hospital lengths of stay that were nearly two times longer than patients without a VAE (28.7 vs 16.6 d; $p = 0.0013$). Boxplots comparing ventilation duration for patients who did and did not experience a VAE are shown in **Figure 2**.

For patients who experienced at least one VAE, the first VAE occurred a median of 5.5 days after the start of ventilation. The first VAE occurrence ranged from 2 to 21 days after the start of the ventilation. **Figure 3** is a Kaplan-Meier plot that illustrates the differences between the Any VAE (red) and No VAEs (blue) groups. The solid lines represent the percentage of patients within that group that had ventilation durations less than or equal to value on the *x*-axis. For the any VAE group, the red dashed line represents the percentage of patients that have not yet experienced their first VAE.

There was no significant difference between the median days spent on the ventilation in the control compared with intervention group patients (7 d [interquartile range (IQR), 4–13 d] vs 8 d [IQR, 5–13 d]; $p = 0.076$). Hospital length of stay was also not significantly different between patients in the control and intervention groups (17.5 d [IQR, 12.0–30.0 d] vs 16.7 d [IQR, 11.8–24.4 d]; $p = 0.31$).

DISCUSSION

After the introduction of a tablet-interface RKP to our institution's critical care department compared with a central workstation RKP, we noted a reduction of overall VAEs (2.0% vs 11.2%; $p = 0.003$), including VACs ($p = 0.002$), IVACs ($p = 0.026$), and PVAPs ($p = 0.036$) (Fig. 1 and Table 1). When compared with patients who experienced no VAE, those with VAEs in this cohort experienced an increased total number of days on the ventilator and longer overall hospital stay (Fig. 2 and Table 2). However, when comparing the

TABLE 2.

Comparison of Ventilation Duration and Hospital Length of Stay for Patients Who Did and Did Not Experience a Ventilator-Associated Event During Their Hospital Stay

Parameter	Any VAE	No VAEs	*p*
Number of patients, *n* (%)	24 (7)	313 (93)	
Ventilation duration, d, median (IQR)	18 (10–26.5)	8 (4–12)	< 0.0001
Hospital length of stay, d, median (IQR)	28.7 (19.0–34.5)	16.6 (11.4–26.0)	0.0013

IQR = interquartile range.

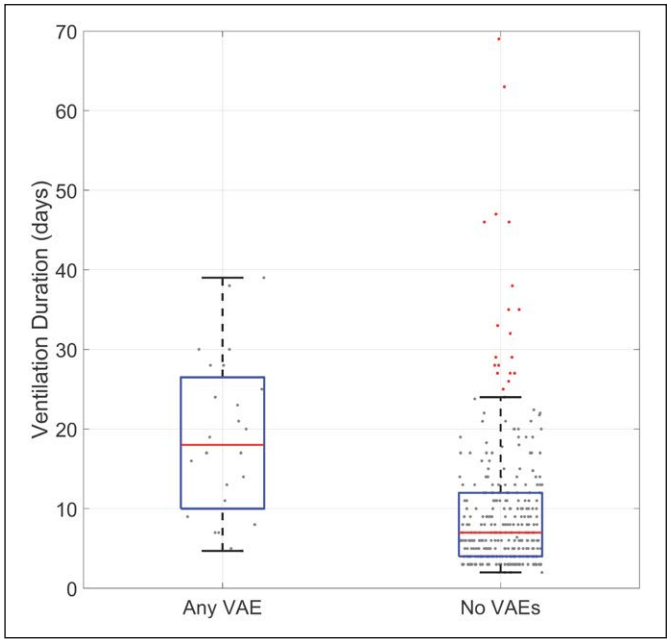

Figure 2. Ventilation duration *boxplots* for patients that did and did not experience a ventilator-associated event (VAE) during their hospital stays. Data from both the control and intervention groups are included. Patients who experienced at least one VAE during their hospital stay had median ventilator duration significantly longer than patients that did not have a VAE (18 vs 7 d; $p <$ 0.0001). *Red line*: median, *blue lines*: interquartile range, *black lines*: most extreme points not considered outliers, *gray points*: individual patient, and *red points*: outliers.

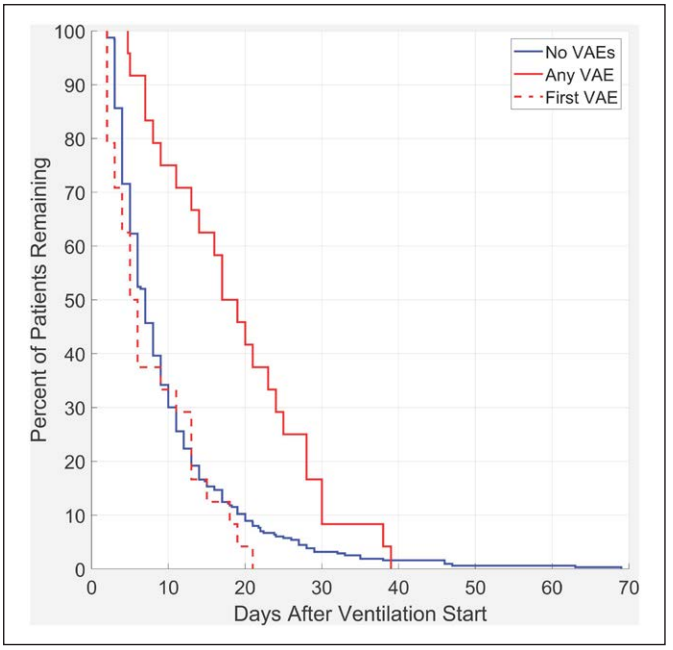

Figure 3. Kaplan-Meier illustrating differences between the any ventilator-associated events (VAEs) (*red*) and no VAEs (*blue*) groups. Data from both the control and intervention groups are included. The *solid lines* represent the percentage of patients within that group that had ventilation durations less than or equal to value on the *x*-axis. *Red dashed line* represents the percentage of patients that have not yet experienced their first VAE within the any VAE group.

central workstation RKP group (control) and the tablet-interface RKP group (intervention), no significant difference was seen with respect to total ventilator days and hospital length of stay. The data analysis includes eight patients who were initially managed without the tablets and were then switched over to management with the tablet interface. We considered removing these patients from the data set before analysis, but there were so few that we included them to avoid bias. None of these patients developed a VAE.

In our ICU, RKP data had been available on all fixed computer workstations, both in the patient room and at the nursing station. The workstations in the patient rooms were frequently inaccessible due to factors such as body fluid precautions, privacy, and family and staff in the room. Therefore, our respiratory therapists generally used the workstations at the nursing station, a significant distance from the bedside. This was thought to be a reason that RKP data was not used to its fullest extent. Because of this issue, we added the tablet computers with RKP data to facilitate its use.

These findings are thought-provoking and not entirely unexpected. When evaluating outcomes in patients who experienced a VAE compared with those without, it is not surprising that there was an increased number of ventilator days and longer hospital length of stay. This is consistent with prior published evidence and remains a strong impetus for clinicians and healthcare systems to put in place organized protocols to minimize the occurrence of VAEs (11). The American College of Chest Physicians and the American Thoracic Society provide guidelines to clinicians on techniques for successful SBTs to facilitate liberation from mechanical ventilation (3, 5), demonstrating a reduction in complications as well as morbidity/mortality (4, 7, 12). The problem herein lies in the ability for an institution to reliably comply with these guidelines, where real-world data shows a significantly smaller improvement in outcomes compared with those performed in these prospective clinical trials (8). RKP effectively focuses on these guidelines and weaning protocols to output critical patient and equipment information to clinicians, allowing them to more easily comply with best practice protocols and decrease adverse events (9). The use of a central workstation RKP, however, may be suboptimal for the multidisciplinary team when rounding, potentially explaining the benefit seen here with a tablet-interface RKP incorporated directly into daily rounds in real-time. The tablet-interface RKP likely allowed clinical teams to better adjust ventilator settings and coordinate earlier successful SBTs compared with the control group; including these parameters into a future study would be critical.

When comparing ventilator days and hospital length of stay between the control and intervention groups, it is at first alarming that no statistical difference is appreciated when a significantly higher number of VAEs occurred in the control group and patients with a VAE had a significantly longer duration of ventilation and hospital length of stay. This is likely due, in this case, to a lack of sample size power to elucidate such a difference, combined with the limitation that patients were not matched based on any severity of illness categorization. Total ventilator days and hospital length of stay when considering the mechanically ventilated patient are highly variable (13), so much so that future research should include matching cohorts based on severity of illness and powering the expected sample size much higher than we did here to accurately distinguish these outcomes when VAEs remain as low as seen in this study (2.0% vs 11.2%).

Our study has some limitations. As a retrospective analysis of data, cause-and-effect relationships are not clear. While it seems logical that providing topical and current data at the point of care to medical decision-makers would improve the outcomes observed here, the mechanism of that improvement is not clear. During the 2 years of the data collection, it is possible that other changes outside the RKP system may have influenced the observed outcomes. Improvements in medications, updated equipment, changes in personnel, and refinements in ventilator protocols may all have played a role. We also do not have data on how frequently the tablet computers were actually used in the management of patients. Future studies should include multiple centers, randomization, blinding, and user feedback. Nonetheless, our findings are compelling and raise important questions that should prompt further evaluation as the RKP system use becomes more widespread in healthcare.

CONCLUSIONS

This observational study suggests that the direct incorporation of RKP into daily multidisciplinary rounds, rather than as a consultant technology at the central workstation, may improve care by decreasing VAEs and potentially improving patient weaning from the ventilator. By having necessary information available at the most time-critical stage in the clinical process (during multidisciplinary rounds), it is likely that increased visibility to a patient's improving or deteriorating physiologic status is readily available and that adherence to best practice weaning protocols, particularly SBTs, are better coordinated within the team. These findings, if noted on a larger scale, could translate significantly to decreased patient morbidity/mortality and reduction in healthcare costs overall. Although the data are encouraging at our institution, further research, both in scale and design, is necessary in order to fully elucidate the true value of RKP as it was designed to perform in this near real-time tablet-interface model.

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