Low Tidal Volume Ventilation Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients

AHRQ Pub. No. 16(17)-0018-5-EF
January 2017

Contents

Introduction

Importance of Low Tidal Volume Ventilation (LTVV) for Mechanically Ventilated Patients

Mechanical ventilation is a lifesaving tool commonly used in intensive care units (ICUs) to support the patient's ability to breathe and oxygenate. Despite this central positive role in patient support, ventilators are also known to cause a number of harms. Among these harms are barotrauma, infection, and "volutrauma."[1] Patients who require mechanical ventilation are often at risk of pulmonary complications. For example, sepsis is the leading cause of acute respiratory distress syndrome (ARDS), and substandard ventilator management can increase the injuries caused by sepsis and other high-risk conditions.[2,3] ARDS has been shown to be underrecognized, undertreated, and associated with a high mortality rate, indicating there exists the potential for improvement in management of these patients.[3] Even patients with limited risk or no underlying pulmonary disease may be harmed by traditional ventilator management strategies.[1,4]

In 2000, the ARDSNet Trial established that a low tidal volume approach significantly improved the outcomes of patients with ARDS as compared with traditional strategies.[2] The ARDSNet protocol focused on maintaining a set tidal volume of 4–6 mL/kg of predicted body weight (PBW) using assist/control mode ventilation and a generous positive end-expiratory pressure (PEEP). A stepwise approach of alternating changes in PEEP and fraction of inspired oxygen (FiO_2) was used for escalation and deescalation of support. The low tidal volume employed prevents overstretching of alveoli (volutrauma), and the generous PEEP both recruits alveoli and prevents alveolar collapse at end-expiration, thereby reducing "atelectrauma" caused by the cycle of collapsing alveoli that then "pop" open.[5] The overall result is less inflammation and damage to the lungs. Gajic et al. suggested that ARDS is an event, similar to ventilator-associated pneumonia (VAP), and high tidal volume is the largest risk factor for hospital-acquired ARDS.[6]

Since the ARDSNet Trial, the concept of LTVV has expanded beyond patients with diagnosed ARDS.[6-11] Results from several randomized controlled trials suggest that for patients without ARDS, the use of tidal volumes in the 6–8 mL/kg PBW range along with the avoidance of zero-end-expiratory pressure (so-called ZEEP)[6-15] and limiting plateau pressures to < 30 cm/H_2O (as compared with 10–12 mL/kg and no specific ZEEP avoidance in most traditional approaches) should be the goal.[16-18] This approach has been shown to be beneficial in patients at risk for ARDS, such as those with sepsis, pneumonia, or traumatic injuries and those requiring massive transfusions.[7,19] In the population of patients with ARDS, the target tidal volume should be between 4 and 6 mL/kg.[20-22] Several studies and reviews have suggested that LTVV may be desirable in virtually all critically ill patients requiring mechanical ventilation.[9,10,19,23] In fact, recent research on high-risk, intraoperative patients undergoing abdominal surgery found significant benefits using a LTVV strategy, suggesting that other patients requiring invasive ventilatory support (distinguished from noninvasive support, such as bilevel positive airway pressure masks) could benefit from a LTVV approach.[24]

In 2008, however, Umoh et al. found that only 46 percent of patients who were eligible to receive LTVV actually did.[25] The implementation of a program that targets the use of LTVV in all patients who are on a ventilator and do not have a contraindication requires a multidisciplinary approach, including collaboration between respiratory therapists, physicians, nurses, and administrators.[26] This guide integrates available resources to help educate and engage all stakeholders. It also proposes protocols to standardize the screening and implementation of LTVV for patients, and tools to evaluate progress.

LTVV as a Preventive Intervention

Prior to 2013, the Centers for Disease Control and Prevention's (CDC) National Healthcare Safety Network's surveillance for ventilator-associated complications was limited to VAP, which is a heterogeneous disease and is difficult to diagnose.[7] A major barrier to standardizing prevention and treatment of VAP is that the radiological and microbiological methods of diagnosing VAP are notoriously subjective and difficult to carry out in critically ill patients. This often results in interobserver variability and inconsistent treatment paradigms. In the United States, the subjectivity in VAP surveillance classification leads to misdiagnosis and treatment errors.[27,28]

In January 2013, the CDC released new surveillance definitions for ventilator-associated events (VAE) and ventilator-associated conditions (VAC). The new, tiered definition is based on objective, streamlined, and automatable criteria; it is more broadly focused on the preventable complications of mechanical ventilation, including VAP.[29] The change in the CDC surveillance definition marks a strong first step toward recognizing the short-term preventable complications associated with mechanical ventilation beyond VAP, and improving outcomes for all mechanically ventilated patients.

In addition to pneumonia, VAC is most commonly attributable to atelectasis, pulmonary edema, and ARDS, acute lung injury, or a combination of these conditions. Recently published data suggest that VAC is associated with prolonged mechanical ventilation, prolonged hospitalization, and increased hospital mortality.[30,31] Thus, preventive interventions must address both VAP and VAC. LTVV, and the implementation of conservative fluid management and restrictive transfusion threshold, is one of the interventions specifically designed to prevent VAC.[8,32,33] LTVV is a key prevention given the emerging evidence linking protective tidal ventilation to decreased incidence of ARDS and decreased time on the ventilator.

What's in the Guide?

By implementing the Low Tidal Volume Ventilation Guide processes into your workflow for ICU patients, your team leads the national effort to reduce complications related to mechanical ventilation and improve physical, cognitive, and psychological patient outcomes. However, this guide alone is not a prescription for success. While this is a model to implement evidence-based practices and improve care for all ICU patients, the authors do not work in your unit. Only your team understands local obstacles and opportunities for improvement for your patients. The materials presented provide a structure to implement evidence-based practices and improve your patients' outcomes. Ultimately, success requires creative energy, profound persistence, strong leadership, and deliberate teamwork.

Using the TRIP Model as a Framework

This guide's structure is based on the model Translating Research Into Practice (TRIP), designed to close the gap between evidence-based guidelines and clinical bedside practice.[34]

The TRIP model has four phases:

1. Develop an evidence-based intervention
    a. Identify interventions associated with improved outcomes
    b. Select interventions with the largest benefit and lowest burden
2. Identify barriers to implementation
3. Measure baseline performance
4. Ensure all patients receive the intervention

Parallel with the technical interventions, the Comprehensive Unit-based Safety Program (CUSP), a frontline-led method to improve the care delivery system, integrates the adaptive elements of patient safety culture. Additional information on CUSP can be found in the Toolkit To Improve Safety for Mechanically Ventilated Patients, in the CUSP Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients.

Implementation of the TRIP and CUSP models has been associated with significant reductions in central line-associated bloodstream infections and VAP in more than 100 Michigan ICUs.[35-38] The Michigan results were sustained for more than 3 years and were associated with a reduction in mortality among Medicare ICUs with significant cost savings.[39,40] Implementation of the same program in Rhode Island ICUs demonstrated similar results.[41] More recently, implementation of the TRIP and CUSP model has been associated with significant reductions in central line-associated bloodstream infections in hospitals in 45 States, from Hawaii to Connecticut.[42] This framework will help you incorporate evidence-based technical and adaptive interventions into your patient care practices.

Phase 1. Develop an Evidence-Based Intervention

In Phase 1, you will develop an evidence-based intervention plan for your work area. Your plan will encompass two distinct processes. First, identify the interventions associated with your desired outcome improvements. Next, select those interventions with the largest benefit and lowest burden.

Identify Interventions Associated With Improved Outcomes

The benefits of LTVV include a reduction of barotrauma, an injury to the lung caused by a change in air pressure, and volutrauma to the lungs, reduced activation of the inflammatory cascades, reduced length of mechanical ventilation, reduced need for reintubation, and reduced hospital length of stay.[10] But what are the key interventions to achieve the implementation of LTVV in all patients in whom it is not contraindicated? A list of interventions based on an extensive review of available literature and guidelines is presented below. Note that recommendations vary in the published protocols, due to small sample sizes and the ongoing evolution of the evidence. Large randomized controlled trials are in process. Therefore, these interventions were selected based on input from national experts in mechanical ventilation in addition to current literature. These interventions form the basis for the Low Tidal Volume Ventilation Data Collection Tool.

Below is a brief overview of other interventions for this safety program. The interventions are examined in the CUSP Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients, the Daily Care Processes Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients, and the Early Mobility Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients:

- ***Multidisciplinary and coordinated approach of care team.*** The joint participation of nurses, physicians, respiratory therapists, and local hospital administrators is vital throughout the TRIP model continuum to create a culture for advocating the use of LTVV for patients. See the CUSP Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients for more information about patient safety culture and multidisciplinary coordination of care.
- ***Structured assessments of sedation level and delirium using scales***. Routinely assessing the patient's cognitive function with these scales will help you target lighter sedation levels and treat delirium. Together with LTVV, these assessments will help you provide better care for your patients, avoid acute lung injury, and get your patients off the ventilator faster. See the Daily Care Processes Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients for more information.
- ***Daily sedation interruption and minimization of sedative use.*** Heavily sedated patients cannot participate in a rehabilitation program, are more likely to suffer delirium, and most important, are slower to achieve extubation. Protocols incorporating daily sedative interruptions and targeting light sedation will help your patients remain alert and cooperative to the extent that they can participate in a rehabilitation program, achieve extubation, and shorten the length of stay in the ICU and hospital. See the Early Mobility

Guide for Reducing Ventilator-Associated Events in Mechanically Ventilated Patients for more information.

Select Interventions With the Largest Benefit and Lowest Burden

While there is no formula for how to approach implementation, your team will want to consider a few factors:

- How much effort is required to build buy-in for the implementation of LTVV?
- Who will champion this effort (a great opportunity for respiratory therapists, and potentially others)?
- How to share the evidence supporting the intervention with the different stakeholders?
- Which resources are required to change current local practice?
- What is required to obtain the necessary resources?

Consider first developing interventions that pursue targets that are "low-hanging fruit" to gain positive momentum before focusing on more challenging interventions. Low-hanging fruit is an intervention that is easy to implement and yields strong rewards. For instance, it would be easier to add a nightlight to bathrooms rather than redesign the floor plan to reduce patient falls. Frontline staff have the wisdom to guide these decisions; focus on their ideas.

Low Tidal Volume Ventilation in Practice

"When I first began working as a respiratory therapist, I was initially employed by a facility that was already utilizing low tidal volume/lung protective ventilation for all patients. As a new hire and new graduate, it was easy to adopt that strategy as the 'norm.' There were frequent discussions and departmental training efforts aimed at focusing the respiratory therapists on the reality of ventilator-induced lung injury. Audits were conducted to evaluate the overall compliance with the lung protective protocol in place.

In addition, the audit findings were frequently shared with staff. If the tidal volume targets/goals were violated, the staff member might be asked to provide rationale for the noncompliance. Frequently, this was due to spontaneously breathing patients on pressure-targeted modes of mechanical ventilation (setting their own volumes). Overall, utilizing low tidal volume strategies for all patients was widely accepted and implemented without debate."

–Respiratory therapist, CUSP team member

Phase 2. Identify Barriers to Implementation

Clinicians want to achieve the best possible outcomes for their patients. If patients are not receiving the evidence-based intervention your team identified, you will need to understand the barriers to compliance.[43] Common barriers to implementation of evidence-based interventions include the three As:

- **Awareness**: Are clinicians aware of the evidence-based intervention?
- **Agreement**: Do clinicians agree with the intervention?
- **Access**: Do clinicians have convenient access to the equipment or supplies required to implement the intervention?

Barriers for implementing the use of a low tidal volume strategy will vary among ICUs. The most commonly encountered barriers include the following:[44,45]

- **Lack of leadership.** Strong leadership is necessary at the institutional level and local unit level, including the recruitment of a multidisciplinary project team. This team should include ALL stakeholders interested in improving patient outcomes:
  - Physicians
  - Nurses and nurse leaders
  - Respiratory, physical, and occupational therapists
  - Representatives from nutrition, pharmacy, and other areas
- **Lack of resources.** Adequate professional staffing and equipment are necessary for successful implementation. Institutional leadership must understand the value of an LTVV program to support implementation in your facility.
- **Lack of education and understanding.** An organized and comprehensive education process should be developed. This process should include the current literature and represent solid evidence supporting the use of a low tidal volume ventilation strategy. Emphasis should be placed on the impact on patient outcomes.
- **Lack of ongoing quality assurance.** Once the strategy is implemented, take measures to assure compliance. Continuing education modules, strategically placed placards, and regular discussion during multidisciplinary rounds will support your ongoing improvement goals.

Through education, engagement, and collaboration of multidisciplinary teams of frontline clinicians, and a strong understanding of the literature and robust quality assurance, these barriers can be surmounted to create a culture where the implementation of LTVV can be implemented and maintained and can result in positive impacts on patient outcomes.

Phase 3. Measure Performance

Baseline Performance

Collect baseline performance data to highlight at-risk areas or your team's improvement opportunities. This data collection is essential to focus your team efforts where they are most likely to yield results. By sharing your results with both clinicians and hospital leadership, you will provide a catalyst for those improvement efforts. There are several potential strategies to assess baseline performance for LTVV:

- Ventilator setting order sets
- Rate of use of tidal volumes of 6–8 mL/kg PBW, or for ARDS patients use of tidal volumes of 4–6 mL/kg PBW
- Rate of use of PEEP settings ≥ 5 cm H_2O
- Barriers to using appropriate settings
- Days of mechanical ventilation
- Appropriate sedation levels to prevent asynchrony
- Adverse events

In addition, you can use implementation information derived from the Exposure Receipt Assessment and Implementation Assessment tools.

Monitor Compliance With Evidence-Based Guidelines

It is important to monitor compliance with evidence-based interventions through frequent formal and informal audits. Share the audit results with all involved staff to maintain engagement and spur improvement. Through this monitoring process, you will be able to maintain awareness, establish expectations, create urgency, generate ownership and accountability, and reward changes in behavior.[38,46] Evaluating performance provides an ongoing, real-time ground truth of performance and outcomes.[47] Areas with poor compliance can be identified and rectified.[48] Any lingering compliance concerns are immediately recognized, allowing the improvement team to revisit. Walk through the process with staff to gain additional insights into barriers to implementation and weak compliance rates.[38]

To collect data and audit compliance, the Low Tidal Volume Ventilation Data Collection Tool includes daily care activities for patients receiving mechanical ventilation to maximize low tidal volume ventilation, including the following:

- Record accurate measurement of height for nomogram-based predicted body weight calculation
- Target a set tidal volume of 6–8 mL/kg PBW in volume cycled modes for patients without ARDS and 4–6 mL/kg PBW for patients with ARDS[50–52]

- Target an approximate volume of 6–8 mL/kg PBW in pressure cycled modes for patients without ARDS and 4–6 mL/kg PBW for patients with ARDS[49-51] and monitor closely so that patients do not exceed these volumes
- Maintain PEEP ≥ 5 cm H_2O unless contraindicated
- Identify patients with ARDS or acute lung injury and patients at high risk for developing ARDS
- Link spontaneous awakening trials and spontaneous breathing trails to facilitate the discontinuation of mechanical ventilation; these are necessary requirements for patients receiving mechanical ventilation and the implementation of the LTVV strategies (more information available in Daily Care Processes and Early Mobility guides)
- Evaluate readiness for discontinuation of mechanical ventilation with daily spontaneous breathing trials (more information available in Daily Care Processes and Early Mobility guides)

Low Tidal Volume Data Collection

The Low Tidal Volume Ventilation Data Collection Tool can be used to collect data on patient care activities. Real-time data to track compliance with interventions should drive all quality improvement efforts.

Tool	*How To Use It*
LTVV Data Collection Tool	Collect actual and target LTVV values, plateau pressure, PEEP value, and ARDS status in order to track LTVV compliance.

Outcomes Reported From Low Tidal Volume Ventilation Data Collection

The following reported outcomes help you monitor patient outcomes to reduce barotrauma volutrauma and atelectrauma to patients' lungs, the activation of the inflammatory cascades, length of mechanical ventilation, need for reintubation, and hospital length of stay:

- Target low tidal volume compliance rate (≥4 and ≤8 mL PBW) (all patients)
- Target low tidal volume compliance rate (≥4 and ≤6 mL PBW) (with ARDS)
- Target low tidal volume compliance rate (≥6 and ≤8 mL PBW) (without ARDS)
- Actual low tidal volume compliance rate (≥4 and ≤8 mL PBW) (all patients)
- Actual low tidal volume compliance rate (≥4 and ≤6 mL PBW) (with ARDS)
- Actual low tidal volume compliance rate (≥6 and ≤8 mL PBW) (without ARDS)
- PEEP compliance rate (≥5 cm H_2O) (all patients)
- PEEP compliance rate (≥5 cm H_2O) (with ARDS)
- PEEP compliance rate (≥5 cm H_2O) (without ARDS)
- Distribution of target tidal volume values (mL PBW) (all patients)
- Distribution of actual tidal volume values (mL PBW) (all patients)

Phase 4. Ensure All Patients Receive the Intervention

Finally, deliver reliable evidence-based care to 100 percent of your patients. Ensure that your interventions become "the way things are done around here." This phase poses the biggest challenge for unit improvement teams. While your team implements phases 1 through 3 of the TRIP model, Phase 4 requires buy-in and engagement from your unit's entire care team and stakeholders. Without full awareness of, agreement with, and access to materials, the interventions will not become the norm and be sustained.

The next section expands on phase 4 of the TRIP framework and operationalizes the 4Es model.

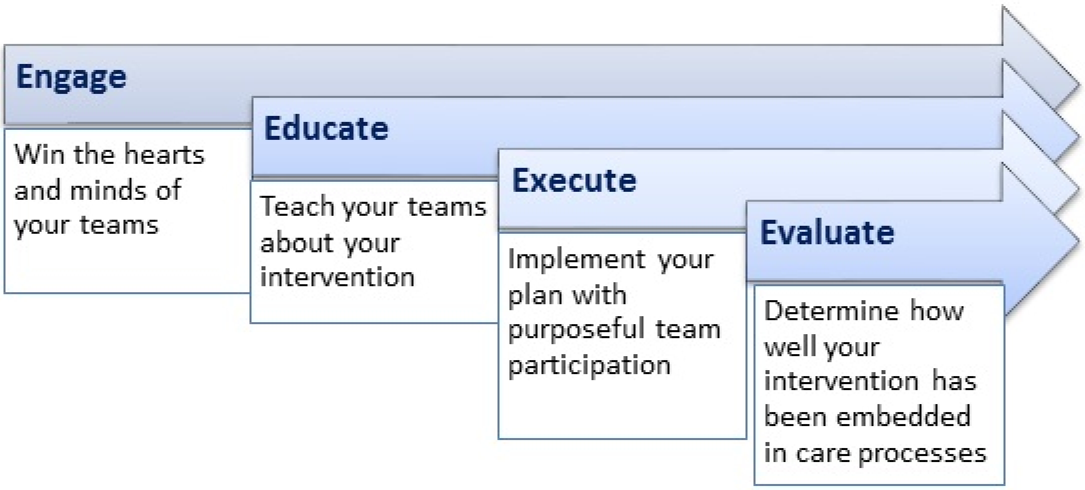
Operationalize the Four Es

Safety efforts succeed through the investment of key stakeholders, including senior leaders, improvement team leaders, and frontline staff. Though stakeholders have different perspectives, hopes, and fears, they often have the same questions about their involvement in the quality improvement process.

Operationalize the Four Es model (Figure 1) by explicitly addressing these associated questions of your key stakeholders:

- **Engage:** How will LTVV improve patient outcomes?
- **Educate**: What do we need to do to implement LTVV with mechanically ventilated patients?
- **Execute**: How will we implement LTVV given local culture and resources?
- **Evaluate**: How will we know our efforts to use LTVV makes a difference?

Figure 1. The 4Es Model



Engage: How Will LTVV Improve Patient Outcomes?

Your staff members are likely overwhelmed by the volume of active quality improvement initiatives in your hospital. You may need to convince them that improving the care of mechanically ventilated patients and including the use of LTVV is not just another request from management. You will need to share the value of using tools to improve the care of mechanically ventilated patients, and to include LTVV. It is important to incorporate LTVV into the routine care of mechanically ventilated patients to help prevent VAC and acute lung injury, shorten the duration of mechanical ventilation, and reduce the patient's length of stay in the ICU and hospital.

Successful implementation of an LTVV program is predicated on a change in both ICU culture and practice. Recruit a champion to meet with and educate stakeholders from various ICU disciplines, thereby building support and addressing anticipated barriers. Sharing patient anecdotes, both success stories and stories of difficult recoveries, is an especially powerful way to engage care providers. Also, invite guest speakers with expertise in the field, visit another hospital with a mature LTVV program, or attend lectures and related conferences to help close the knowledge and training gap.[45]

Engage Senior Executives

In addition, designate a medical director for LTVV to advocate for resources and address barriers, whether global, discipline based, or patient-centric. This executive attends regular interdisciplinary meetings, helps prioritize compliance for eligible patients, and employs organizational support and resources on behalf of LTVV efforts. You can garner executive support by stressing the positive impacts of LTVV:

- Protect from barotrauma and volutrauma
- Decrease VAC
- Decrease duration of ventilation
- Decrease ICU length of stay
- Decrease hospital length of stay

Make Performance More Visible

Quality improvement teams often share process and outcome performance measures with select individuals or improvement groups within their organization. Key stakeholders, including frontline staff and senior leadership, are often unaware of local performance. If you were to ask frontline staff and leadership their VAE rates or their compliance rate with LTVV measures, would they know the answer? In most cases, they would not. Frontline clinicians cannot own their data if they have no exposure to their data.

Give your invested stakeholders feedback by sharing your performance in these ways:

- Post a trend line of the daily rate of LTVV compliance in your unit so frontline staff (including respiratory therapists, nurses, and physicians) can see changes over time
- Benchmark your performance against similar hospitals

Most importantly, performance feedback will only be meaningful if your providers believe the data are valid. Be transparent about your data collection techniques, analyses, and any efforts your team has made to address possible biases.

Recognize Staff Efforts

Financial incentives to engage staff and leaders, while attractive, are often not feasible or sustainable. Staff recognition with nonfinancial strategies is also an effective way to engage colleagues.

Some examples include—

- Assign a title for key team participants, such as the respiratory therapist, physician, or nurse project leader. Make new designations visible by posting around the unit and by publishing in a hospitalwide newsletter or Web site.
- Encourage team members to present their efforts on a recurring basis at important committee or board meetings within your organization, or even at regional or national conferences if applicable.
- Highlight staff efforts in local newsletters, bulletins, or publications.

Educate: What Do We Need To Do To Implement LTVV for Mechanically Ventilated Patients?

Evidence To Support the Use of LTVV

The concept of LTVV has been expanded beyond patients with diagnosed ARDS.[6-11] The goal for patients without ARDS in this program is the use of tidal volumes in the 6–8 mL/kg PBW range along with the avoidance of ZEEP[6-13,24] and limiting plateau pressures to < 30 cm H_2O.[8-11] Traditional approaches use 10–12 mL/kg without specific ZEEP avoidance.[16-18] The LTVV approach has been shown to benefit patients at risk for ARDS, such as those with sepsis, pneumonia, or traumatic injuries, and patients requiring massive transfusions.[7,19] Recent randomized controlled trials of patients without ARDS undergoing abdominal surgery found significant benefits using a LTVV strategy.[8,9] Based on these studies and multiple retrospective analyses, LTVV has been advocated as desirable in virtually all critically ill patients requiring mechanical ventilation.[6,10]

In the population of patients with ARDS, the target tidal volume should be 4–6 mL/kg PBW as opposed to the 6–8 mL/kg PBW range.[20-22]

Many patients admitted to the ICU already have risk factors for ARDS, such as pneumonia, sepsis, noncardiogenic shock, trauma, multiple transfusions, or cardiopulmonary bypass.[2] Mechanical ventilation with high tidal volumes can amplify inflammatory responses, ultimately leading to ARDS.[6,33,52,53] Studies comparing protective ventilation with conventional or traditional ventilation have shown a beneficial impact of the protective ventilation on inflammation, oxygenation, and/or clinical outcome data.[10,11,33,52,54-71]

Often ventilator settings for individual cases are not changed from the initial settings. These may have been set based on physician preference or emergent conditions when pertinent information such as height may not have been available.[10,52] Pulmonary damage can actually occur after only a few hours of mechanical ventilation.[10,52] Therefore, it is important that LTVV be implemented if at all possible **at the time of initial intubation** to reduce the likelihood of developing ARDS.[12] If actual height is not known at the time of intubation due to emergent circumstances, this information should be ascertained as soon as possible with immediate adjustments in tidal volume as appropriate. The use of a tidal volume of 6–8 mL/kg PBW in patients without ARDS can be used safely and with protective benefits.[10,33,52,54-69,71-73]

Initiating Low Tidal Volume Ventilation

Tidal volume should be based upon PBW. It has been shown that when tidal volume is based on clinician estimation of need or visual estimation of height, it is frequently overestimated,[53] especially in shorter obese female patients.[13,74,75]

To calculate predicted body weight (PBW) mL/kg—

1. PBW (male) = 50 + [height (inches) – 60 X 2.3]
2. PBW (female) = 45.5 + [height (inches) – 60 X 2.3]

For transgender or transsexual patients, use the gender of origin, not their current gender.

As a quick reference, Table 1 and Table 2 are available. They are also available as a pocket guide for clinicians to quickly determine tidal volume. See the Daily LTVV Data Collection Tool.

Table 1. Female Quick Reference for Tidal Volume

FEMALE QUICK REFERENCE FOR TIDAL VOLUME					
HEIGHT	**INCHES**	**PBW**	**8 mL/KG**	**6 mL/KG**	**4 mL/KG**
4'6"	54	31.7	260	190	130
4'7"	55	34.0	270	210	140
4'8"	56	36.3	290	220	150
4'9"	57	38.6	310	230	160
4'10"	58	40.9	330	250	170
4'11"	59	43.2	350	260	180
5'0"	60	45.5	370	280	180
5'1"	61	47.8	380	290	190
5'2"	62	50.1	400	300	200
5'3"	63	52.4	420	320	210
5'4"	64	54.7	440	330	220
5'5"	65	57.0	460	340	230
5'6"	66	59.3	480	360	240
5'7"	67	61.6	500	370	250
5'8"	68	63.9	510	390	260
5'9"	69	66.2	530	400	270
5'10"	70	68.5	550	410	280
5'11"	71	70.8	570	430	290
6'0"	72	73.1	590	440	290
6'1"	73	75.4	610	450	300
6'2"	74	77.7	620	470	310
6'3"	75	80.0	640	480	320
6'4"	76	82.3	660	500	330

KG = kilogram; mL = milliliter; PBW = predicted body weight

Table 2. Male Quick Reference for Tidal Volume

MALE QUICK REFERENCE FOR TIDAL VOLUME					
HEIGHT	**INCHES**	**PBW**	**8 mL/KG**	**6 mL/KG**	**4 mL/KG**
4'6"	54	36.2	290	220	150
4'7"	55	38.5	310	230	160
4'8"	56	40.8	330	250	170
4'9"	57	43.1	350	260	170
4'10"	58	45.4	370	270	180
4'11"	59	47.7	380	290	190
5'0"	60	50.0	400	300	200
5'1"	61	52.3	420	320	210
5'2"	62	54.6	440	330	220
5'3"	63	56.9	460	340	230
5'4"	64	59.2	480	360	240
5'5"	65	61.5	490	370	250
5'6"	66	63.8	510	390	260
5'7"	67	66.1	530	400	270
5'8"	68	68.4	550	410	280
5'9"	69	70.7	570	430	290
5'10"	70	73.0	590	440	290
5'11"	71	75.3	600	450	300
6'0"	72	77.6	620	470	310
6'1"	73	79.9	640	480	320
6'2"	74	82.2	660	500	330
6'3"	75	84.5	680	510	340
6'4"	76	86.8	700	520	350

KG = kilogram; mL = milliliter; PBW = predicted body weight

Initial Ventilator Settings

After you determine the appropriate tidal volume, adjust the tidal volume to 6 mL/kg of predicted body if already on mechanical ventilation. If the tidal volume is greater than 8 mL/kg, the tidal volume should be reduced over 2 hours. The respiratory rate should be adjusted to maintain the same minute ventilation as tidal volume is decreased.

Subsequent Ventilator Settings: Acid-Base Goals

Acceptable pH for patients receiving LTVV is a pH 7.30–7.45. The notable exception is traumatic brain injury patients, in whom hypercapnia may result in an inadvertent reduction in cerebral blood flow. Hypercapnia refers to excessive carbon dioxide in the bloodstream, typically caused by inadequate respiration. See below if outside of the acceptable pH range:

- **pH < 7.15** that has not responded to a respiratory rate of 35 breaths per minute and bicarbonate was tried or considered. Increase tidal volume by 0.5 mL/kg PBW until pH > 7.15. In this case plateau pressure (P_{STAT}) may exceed 30 cm H_2O.
- **pH 7.15–7.29**. Increase respiratory rate to a maximum of 35 breaths per minute.
- **pH > 7.45**. Decrease respiratory rate if patient is not overbreathing set rate.

Ongoing Tidal Volume Management

The goal is to achieve a tidal volume of 6 mL/kg of predicted body weight. This will offer the greatest protection against ventilator induced lung injury.

1. Maintain airway plateau pressure, or $P_{PLAT} \leq 30$ cm H_2O.
2. Routinely assess the P_{PLAT} with every ventilator assessment and after every tidal volume or PEEP adjustment.
3. If the patient's P_{PLAT} is > 30 cm H_2O for at least two ventilator assessments, decrease the tidal volume by 0.5 mL/kg every 60 minutes until the P_{PLAT} is ≤ 30 cm H_2O. Do not reduce the tidal volume below 4 mL/kg PBW.
4. If the patient is uncomfortable or is experiencing patient-ventilator asynchrony despite other appropriate ventilator adjustments, consider adjusting the tidal volume as follows: if the tidal volume is < 6 mL/kg and P_{PLAT} is < 25 cm H_2O for at least two successive ventilator assessments, then increase the tidal volume by 0.5 mL/kg every 30 minutes until the tidal volume reaches 6 mL/kg as long as the P_{PLAT} remains ≤ 30 cm H_2O. Please note that if the patient is adequately ventilated and comfortable without deep sedation, these adjustments are not necessary.
5. Meet these oxygenation goals:
    1. Keep the PaO_2 between 55 mm Hg and 80 mm Hg or the SpO_2 between 88 percent and 95 percent.
    2. Consider use of PEEP/FiO_2 ladders[76] (Table 3) to assist with oxygenation, especially in patients with ARDS.

Table 3. PEEP/FiO_2 Ladders

LOWER PEEP/HIGHER FIO2

Fi02	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1.0
PEEP	5	5	8	8	10	10	10	12	14	14	14	16	18	18–24

HIGHER PEEP/LOWER FIO2

Fi02	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5–0.8	0.8	0.9	1.0	1.0
PEEP	5	8	10	12	14	14	16	16	18	20	22	22	22	24

Getting Your Message to Frontline Staff

Your team will need to educate staff and leadership about the evidence, explain new processes, answer questions, and set performance goals. Workshops, hands-on trainings, conferences, slide presentations, and interactive discussions are all effective tools to use for staff education. In fact, multiple teaching modalities can meet diverse learning styles.[77,78] Local champions and topic experts should be responsible for staff education[25,46,79] that should include both multidisciplinary and specialty-targeted educational programs.[25,46,79-81] Sessions must be informative and relevant for the learner, providing clear explanation of desired procedures. These sessions explain why staff members need to adopt the new practices and allow dialogue. Done well, the session should engage and encourage adoption of new practices.[46,78]

Physician Education Efforts

While educational sessions should be interdisciplinary, some groups are more receptive to educators from their own groups, such as physicians. The physician champion on your safety program team can lead breakout physician education efforts. Several education strategies described in the literature focus on changing physician behavior:

- Provide physicians with educational information packets consisting of research literature, evidence-based reviews, hospital specific data, and national guidelines. Education information from national physician professional societies is particularly useful.
- Introduce educational information at staff meetings or grand rounds.
- Utilize informal educational meetings and networks to disseminate information.
- Conduct educational outreach visits involving content experts, such as respiratory therapists, pharmacists, pulmonologists, and infection preventionists.

Execute: How Will We Implement LTVV Given Local Culture and Resources?

Frame Your Intervention in the Science of Safety

Without a doubt, clinicians care deeply about their patients. Yet we are all fallible. No matter how hard we try, we will forget to order an important medication, or we will make other mistakes. Patient safety research has demonstrated consistently that blaming individual providers will not prevent patient harm. Organization-level factors, functional work area-related factors, team-related factors, task-related factors, and patient-related factors all have a role in patient outcomes. We need to ensure our system is designed to deliver these evidence-based interventions for every patient, every time.

Apply Principles of Safe System Design

Every system is perfectly designed to produce the results it delivers. If we want to achieve substantive and sustainable improvements in patient outcomes, we have to change the flawed components of the systems in which clinicians work. We must redesign systems to consistently produce wellness instead of harm. Other critical industries, like airlines and nuclear energy, teach us clear principles of safe system design:

- Standardize care
- Create independent checks
- Learn from defects

Standardize Care

Standardizing care and reducing complexity helps to establish new care processes as "normal behavior" for staff.[82] A way to incorporate standardization into patient care is to use daily multidisciplinary rounds. Daily rounds should follow a structured format:

- Discuss the patient's goals for that day;
- Determine what resources and actions are necessary to achieve those goals; and
- Close any communication gaps regarding care.

Any potential barriers and/or any safety issues should be identified.[39,47,83] Providers want to do the right thing for their patients. However, the care of a patient on mechanical ventilation is complex. It is difficult to execute every evidence-based care practice in real time without clear communication and standardized care procedures.

Create Independent Checks

Creating independent checks or redundancy along the continuum of care involves developing unique and separate system checks for critical procedures. High-reliability industries, like the airline and nuclear energy industries mentioned above, use independent redundancies to monitor the high-risk procedures most likely to cause harm if not done correctly or not completed. The health care industry is now developing independent redundancies. By combining both education and redundancy, we can significantly improve the processes of care.[83]

Engaging all caregivers in care choices, including respiratory, physical, and occupational therapists, provides a powerful independent redundancy.

One powerful strategy to standardize care, reduce complexity, and create independent checks such that patients will reliably receive evidence-based interventions is the Low Tidal Volume Ventilation Data Collection Tool. This tool is completed daily for every patient on mechanical ventilation. We encourage you to explore this tool as you promote and implement LTVV initiatives.

In the following sections we provide several strategies for standardizing care, reducing complexity and creating independent checks. Talk to your frontline providers! They likely have many other suggestions for creating a safer system design to ensure patients receive necessary interventions.

Learn From Defects

Learning from defects provides a detailed process to improve your systems.[82, 84, 85] A defect is anything you do not want to happen again, such as an unsafe condition, a patient fall, a venous thromboembolism, a medication error, missing equipment, or a ventilator-associated event.[86] There are different problem-solving approaches to addressing defects:

- **First-order problem solving** (also known as “the workaround”).[86,87] Often used because it is the fastest solution, this approach solves the problem for one patient but does not reduce the risk for future patients.
- **Second-order problem solving.**[82,86] Reducing risks for future patients by improving systems, this is the proactive approach. It typically requires some analysis to determine all of the factors contributing to the defect.

In order to learn from defects, we need a shift in perspective—an attitude that errors and near misses have something to teach us about how we can improve our systems.[87-89]

The CUSP Learn From Defects Tool provides a framework that will guide you through a second-order problem-solving approach. You will identify system factors that contribute to defects, plan improvements, and sustain those improvements through four questions:

- What happened?
- Why did it happen?
- How will you reduce the risk of the defect happening again?
- How will you know the risk is reduced?

Strategies for Safe System Design Principles

Here are strategies to standardize care and create independent checks in implementing an LTVV program:

- Most important is to ensure that patients are put on the appropriate LTVV protocol at intubation
- Incorporate Daily Goals Checklist to reliably address LTVV for every mechanically ventilated patient on rounds
- Change respiratory therapy reporting
  - Assure that LTVV is addressed for every mechanically ventilated patient
  - Add LTVV reporting to the electronic medical record
- Hold daily ventilator setting huddles midday with the ICU physician, respiratory therapist, and charge nurse to ensure patient tidal volume and other ventilation targets are achieved
- Provide pocket quick reference cards to facilitate LTVV (located in Tables 1 and 2, and at the end of the Daily LTVV Data Collection Tool)
- Inform family members about LTVV and how using this method can reduce the chance of acute lung injury and shorten the amount of time their loved one may spend on mechanical ventilation
- Incorporate LTVV outcomes into ICU dashboards

Check Current Policies

Policies can be an effective strategy to improve compliance with evidence-based practice. Historically, unit and hospital policies tend to prefer a higher volume ventilation strategy for their mechanically ventilated patients. Check your hospital or unit policies, protocols, or standard order sets, which might inhibit the use of LTVV. We encourage you to review and update your existing policies to promote LTVV in your ICU.

Evaluate: How Will We Know Our Efforts Make a Difference?

The final step in the Four Es model is to evaluate the impact of your interventions. You need to assess whether your efforts are adding value for your staff, your patients, and their families.

Conducting frequent formal and informal audits with continuous timely feedback of outcome measures to all staff involved in this quality improvement process is essential. To accomplish this, we recommend that you monitor and report back to your staff each month. Routinely reporting results allows staff to track improvements in performance, reminds staff about the new processes, and even motivates improvement.[46] Be sure to celebrate your successes!

Low Tidal Volume Ventilation in Practice

"About a year ago, our facility hired a nurse trained in quality and patient safety. This patient safety nurse audits the daily charts to verify specific care requirements or interventions were completed; she also noted when cases were compliant with protocols.

Any issue involving compliance with care procedures or evidence-based interventions raises a flag. She sets up hands-on education with the involved staff members. In addition, she aligns her schedule to the next shift of those providers to reeducate and address lingering questions. We have added the low tidal volume ventilation measures to her audit and education activities. Staff appreciates the fast feedback and individual opportunity to ask questions."

–CUSP team member

LTVV Tools

Tools	*How To Use Them*
LTVV Fact Sheet	Senior executives can use to note patient safety issues observed during safety rounds.
LTVV Literature Review	This 6½-minute video focuses on how engaging a senior executive to partner with a unit will bridge the gap between senior management and frontline providers and will facilitate a system-level perspective on quality and safety challenges that exist at the unit level.

References

1. Ware LB, Matthay MA. The acute respiratory distress syndrome. N Engl J Med. 2000 May;342(18):1334-49. PMID: 10793167.

2. ARDS Definition Task Force, Ranieri VM, Rubenfeld GD, et al. Acute respiratory distress syndrome: The berlin definition. JAMA. 2012 Jun;307(23):2526-2533. PMID: 22797452.

3. Bellani G, Laffey JG, Pham T, et al. Epidemiology, patterns of care, and mortality for patients with acute respiratory distress syndrome in intensive care units in 50 countries. JAMA. 2016 Feb;315(8):788-800. PMID: 26903337.

4. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. The Acute Respiratory Distress Syndrome Network. N Engl J Med. 2000 May;342(18):1301-8. PMID: 10793162.

5. Slutsky AS, Ranieri VM. Mechanical ventilation: Lessons from the ARDSNet trial. Respir Res. 2000 ;1(2):73-7. PMID: 11667968.

6. Gajic O, Frutos-Vivar F, Esteban A, et al. Ventilator settings as a risk factor for acute respiratory distress syndrome in mechanically ventilated patients. Intensive Care Med. 2005 Jul;31(7):922-6. PMID: 15856172.

7. Allison MG, Scott MC, Hu KM, et al. High initial tidal volumes in emergency department patients at risk for acute respiratory distress syndrome. J Crit Care. 2015 Apr;30(2):341-3. PMID: 25630953.

8. Futier E, Constantin JM, Paugam-Burtz C, et al. A trial of intraoperative low-tidal-volume ventilation in abdominal surgery. N Engl J Med. 2013 Aug;369(5):428-37. PMID: 23902482.

9. Severgnini P, Selmo G, Lanza C, et al. Protective mechanical ventilation during general anesthesia for open abdominal surgery improves postoperative pulmonary function. Anesthesiology. 2013 Jun;118(6):1307-21. PMID: 23542800.

10. Lellouche F, Dionne S, Simard S, et al. High tidal volumes in mechanically ventilated patients increase organ dysfunction after cardiac surgery. Anesthesiology. 2012 May;116(5):1072-82. PMID: 22450472.

11. Sundar S, Novack V, Jervis K, et al. Influence of low tidal volume ventilation on time to extubation in cardiac surgical patients. Anesthesiology. 2011 May;114(5):1102-10. PMID: 21430518.

12. Metnitz PG, Metnitz B, Moreno RP, et al. Epidemiology of mechanical ventilation: Analysis of the SAPS 3 database. Intensive Care Med. 2009 May;35(5):816-25. PMID: 19288079.

13. Marangoni E, Alvisi V, Ragazzi R, et al. Respiratory mechanics at different PEEP level during general anesthesia in the elderly: A pilot study. Minerva Anestesiol. 2012 Nov;78(11):1205-14. PMID: 2272859.

14. Santa Cruz R, Rojas JI, Nervi R, et al. High versus low positive end-expiratory pressure (PEEP) levels for mechanically ventilated adult patients with acute lung injury and acute respiratory distress syndrome. Cochrane Database Syst Rev. 2013 Jun;6:CD009098. PMID: 23740697.

15. Manzano F, Fernandez-Mondejar E, Colmenero M, et al. Positive-end expiratory pressure reduces incidence of ventilator-associated pneumonia in nonhypoxemic patients. Crit Care Med. 2008 Aug;36(8):2225-31. PMID: 18664777.

16. Chan MC, Tseng JS, Chiu JT, et al. Prognostic value of plateau pressure below 30 cm H2O in septic subjects with acute respiratory failure. Respir Care. 2015 Jan;60(1):12-20. PMID: 25249650.

17. Jaswal DS, Leung JM, Sun J, et al. Tidal volume and plateau pressure use for acute lung injury from 2000 to present: A systematic literature review. Crit Care Med. 2014 Oct;42(10):2278-89. PMID: 25098333.

18. Kilickaya O, Gajic O. Initial ventilator settings for critically ill patients. Crit Care. 2013 Mar;17(2):123. PMID: 23510269.

19. Pannu SR, Hubmayr RD. Safe mechanical ventilation in patients without ARDS. Minerva Anestesiol. 2015 Jan. PMID: 25598293.

20. Chen L, Brochard L. Lung volume assessment in acute respiratory distress syndrome. Curr Opin Crit Care. 2015 Jun;21(3):259-64. PMID: 25827524.

21. Luks AM. Ventilatory strategies and supportive care in acute respiratory distress syndrome. Influenza Other Respir Viruses. 2013 Nov;7 Suppl 3:8-17. PMID: 24215377.

22. Retamal J, Libuy J, Jimenez M, et al. Preliminary study of ventilation with 4 ml/kg tidal volume in

acute respiratory distress syndrome: Feasibility and effects on cyclic recruitment - derecruitment and hyperinflation. Crit Care. 2013 Jan;17(1):R16. PMID: 23351488.

23. Serpa Neto A, Simonis FD, Barbas CS, et al. Lung-protective ventilation with low tidal volumes and the occurrence of pulmonary complications in patients without acute respiratory distress syndrome: A systematic review and individual patient data analysis. Crit Care Med. 2015 Jul,15. PMID: 26181219.

24. PROVE Network Investigators for the Clinical Trial Network of the European Society of Anaesthesiology, Hemmes SN, Gama de Abreu M, et al. High versus low positive end-expiratory pressure during general anaesthesia for open abdominal surgery (PROVHILO trial): A multicentre randomised controlled trial. Lancet. 2014 Aug;384(9942):495-503. PMID: 24894577.

25. Umoh NJ, Fan E, Mendez-Tellez PA, et al. Patient and intensive care unit organizational factors associated with low tidal volume ventilation in acute lung injury. Crit Care Med. 2008 May;36(5):1463-8. PMID: 18434907.

26. Bigham MT, Amato R, Bondurrant P, et al. Ventilator-associated pneumonia in the pediatric intensive care unit: Characterizing the problem and implementing a sustainable solution. *J* Pediatr. 2009 Apr;154(4):582-7.e2. PMID: 19054530.

27. Klompas M. Ventilator-associated events surveillance: A patient safety opportunity. Curr Opin Crit Care. 2013 Feb;19(5):424-31. PMID: 25369558.

28. Lambert ML, Silversmit G, Savey A, et al. Preventable proportion of severe infections acquired in intensive care units: Case-mix adjusted estimations from patient-based surveillance data. Infect Control Hosp Epidemiol. 2014 May;35(5):494-501. PMID: 24709717.

29. Klompas M, Anderson D, Trick W, et al. The preventability of ventilator-associated events. the CDC prevention epicenters wake up and breathe collaborative. Am J Respir Crit Care Med. 2015 Feb;191(3):292-301. PMID: 25369558.

30. Klompas M, Kleinman K, Murphy MV. Descriptive epidemiology and attributable morbidity of ventilator-associated events. Infect Control Hosp Epidemiol. 2014 May;35(5):502-10. PMID: 24709718.

31. Muscedere J, Sinuff T, Heyland DK, et al. The clinical impact and preventability of ventilator-associated conditions in critically ill patients who are mechanically ventilated. Chest. 2013 Nov;144(5):1453-60. PMID: 24030318.

32. Klompas M, Branson R, Eichenwald EC, et al. Strategies to prevent ventilator-associated pneumonia in acute care hospitals: 2014 update. Infect Control Hosp Epidemiol. 2014 Aug;35(8):915-36. PMID: 25026607.

33. Determann RM, Royakkers A, Wolthuis EK, et al. Ventilation with lower tidal volumes as compared with conventional tidal volumes for patients without acute lung injury: A preventive randomized controlled trial. Crit Care. 2010;14(1):R1. PMID: 20055989.

34. Pronovost PJ, Berenholtz SM, Needham DM. Translating evidence into practice: A model for large scale knowledge translation. BMJ. 2008 Oct:337:963-5. PMID: 18838424.

35. Pronovost PJ, Murphy DJ, Needham DM. The science of translating research into practice in intensive care. Am J Respir Crit Care Med. 2010 Dec;182(12):1463-4. PMID: 21159904.

36. Pronovost P, Needham D, Berenholtz S, et al. An intervention to decrease catheter-related bloodstream infections in the ICU. N Engl J Med. 2006 Dec;355(26):2725-32. PMID: 17192537.

37. Pronovost PJ, Goeschel CA, Colantuoni E, et al. Sustaining reductions in catheter related bloodstream infections in Michigan intensive care units: Observational study. BMJ. 2010 Feb;340:c309. PMID: 20133365.

38. Berenholtz SM, Pham JC, Thompson DA, et al. Collaborative cohort study of an intervention to reduce ventilator-associated pneumonia in the intensive care unit. Infect Control Hosp Epidemiol. 2011 Apr;32(4):305-14. PMID: 21460481.

39. Lipitz-Snyderman A, Steinwachs D, Needham DM, et al. Impact of a statewide intensive care unit quality improvement initiative on hospital mortality and length of stay: Retrospective comparative analysis. BMJ. 2011 Jan;342:d219. PMID: 21282262.

40. Waters HR, Korn R,Jr, Colantuoni E, et al. The business case for quality: Economic analysis of the Michigan Keystone Patient Safety Program in ICUs. Am J Med Qual. 2011 Sep-Oct;26(5):333-9. PMID: 21856956.

41. DePalo VA, McNicoll L, Cornell M, et al. The Rhode Island ICU collaborative: A model for reducing central line-associated bloodstream infection and

ventilator-associated pneumonia statewide. Qual Saf Health Care. 2010 Dec;19(6):555-61. PMID: 21127114.

42. Berenholtz SM, Lubomski LH, Weeks K, et al. Eliminating central-line associated bloodstream infections: A national patient safety imperative Infect Control Hosp Epidemiol. 2014 Jan;1(35):56-62. PMID: 24334799.

43. Gurses AP, Murphy DJ, Martinez EA, et al. A practical tool to identify and eliminate barriers to compliance with evidence-based guidelines. Jt Comm J Qual Patient Saf. 2009 Oct;35(10):526-32, 485. PMID: 19886092.

44. Biehl M, Kashiouris MG, Gajic O. Ventilator-induced lung injury: Minimizing its impact in patients with or at risk for ARDS. Respir Care. 2013 Jun;58(6):927-37. PMID: 23709192.

45. Mikkelsen ME, Dedhiya PM, Kalhan R, et al. Potential reasons why physicians underuse lung-protective ventilation: A retrospective cohort study using physician documentation. Respir Care. 2008 Apr;53(4):455-61. PMID: 18364057.

46. Hatler CW, Mast D, Corderella J, et al. Using evidence and process improvement strategies to enhance healthcare outcomes for the critically ill: A pilot project. Am J Crit Care. 2006 Nov;6(15):549-55. PMID: 17053262.

47. Krimsky WS, Mroz IB, McIlwaine JK, et al. A model for increasing patient safety in the intensive care unit: Increasing the implementation rates of proven safety measures. Qual Saf Health Care. 2009 Feb;18(1):74-80. PMID: 19204137.

48. Westwell S. Implementing a ventilator care bundle in an adult intensive care unit. Nurs Crit Care. 2008 Jul-Aug;13(4):203-7. PMID: 18577172.

49. Putensen C, Muders T, Kreyer S, et al. Lung protective ventilation - protective effect of adequate supported spontaneous breathing. Anasthesiol Intensivmed Notfallmed Schmerzther. 2008 Jun;43(6):456-62; quiz 463. PMID: 18563674.

50. Dellinger RP, Vincent JL, Marshall J, et al. Important issues in the design and reporting of clinical trials in severe sepsis and acute lung injury. J Crit Care. 2008 Dec;23(4):493-9. PMID: 19056012.

51. Girard TD, Bernard GR. Mechanical ventilation in ARDS: A state-of-the-art review. Chest. 2007 Mar;131(3):921-9. PMID: 17356115.

52. Gajic O, Dara SI, Mendez JL, et al. Ventilator-associated lung injury in patients without acute lung injury at the onset of mechanical ventilation. Crit Care Med. 2004 Sep;32(9):1817-24. PMID: 15343007.

53. Linares-Perdomo O, East TD, Brower R, et al. Standardizing predicted body weight equations for mechanical ventilation tidal volume settings. Chest. 2015 Jul;148(1):73-8. PMID: 25741642.

54. Wrigge H, Putensen C. What is the "best PEEP" in chronic obstructive pulmonary disease? Intensive Care Med. 2000 Sep;26(9):1167-9. PMID: 11089736.

55. Chaney MA, Nikolov MP, Blakeman BP, et al. Protective ventilation attenuates postoperative pulmonary dysfunction in patients undergoing cardiopulmonary bypass. J Cardiothorac Vasc Anesth. 2000 Oct;14(5):514-518. PMID: 11052430.

56. Koner O, Celebi S, Balci H, et al. Effects of protective and conventional mechanical ventilation on pulmonary function and systemic cytokine release after cardiopulmonary bypass. Intensive Care Med. 2004;30(4):620-6. PMID: 14722635.

57. Wrigge H, Uhlig U, Zinserling J, et al. The effects of different ventilatory settings on pulmonary and systemic inflammatory responses during major surgery. Anesth Analg. 2004 Mar;98(3):775-81, table of contents. PMID: 14980936.

58. Schilling T, Kozian A, Huth C, et al. The pulmonary immune effects of mechanical ventilation in patients undergoing thoracic surgery. Anesth Analg. 2005 Oct;101(4):957-65, table of contents. PMID: 16192502.

59. Wrigge H, Zinserling J, Neumann P, et al. Spontaneous breathing with airway pressure release ventilation favors ventilation in dependent lung regions and counters cyclic alveolar collapse in oleic-acid-induced lung injury: A randomized controlled computed tomography trial. Crit Care. 2005;9(6):R780-9. PMID: 16356227.

60. Reis Miranda D, Gommers D, Struijs A, et al. Ventilation according to the open lung concept attenuates pulmonary inflammatory response in cardiac surgery. Eur J Cardiothorac Surg. 2005 Dec;28(6):889-95. PMID: 16271479.

61. Zupancich E, Paparella D, Turani F, et al. Mechanical ventilation affects inflammatory mediators in patients undergoing cardiopulmonary bypass for cardiac surgery: a randomized clinical

trial. J Thorac Cardiovasc Surg. 2005 Aug;130(2):378-83. PMID: 16077402.

62. Fernandez-Perez ER, Keegan MT, Brown DR, et al. Intraoperative tidal volume as a risk factor for respiratory failure after pneumonectomy. Anesthesiology. 2006 Jul;105(1):14-8. PMID: 16809989.

63. Choi G, Wolthuis EK, Bresser P, et al. Mechanical ventilation with lower tidal volumes and positive end-expiratory pressure prevents alveolar coagulation in patients without lung injury. Anesthesiology. 2006 Oct;105(4):689-95. PMID: 17006066.

64. Michelet P, D'Journo XB, Roch A, et al. Protective ventilation influences systemic inflammation after esophagectomy: A randomized controlled study. Anesthesiology. 2006 Nov;105(5):911-9. PMID: 17065884.

65. Licker M, Diaper J, Villiger Y, et al. Impact of intraoperative lung-protective interventions in patients undergoing lung cancer surgery. Crit Care. 2009;13(2):R41. PMID: 19317902.

66. Weingarten TN, Whalen FX, Warner DO, et al. Comparison of two ventilatory strategies in elderly patients undergoing major abdominal surgery. Br J Anaesth. 2010 Jan;104(1):16-22. PMID: 19933173.

67. Yang M, Ahn HJ, Kim K, et al. Does a protective ventilation strategy reduce the risk of pulmonary complications after lung cancer surgery?: A randomized controlled trial. Chest. 2011 Mar;139(3):530-7. PMID: 20829341.

68. Lee PC, Helsmoortel CM, Cohn SM, et al. Are low tidal volumes safe? Chest. 1990 Feb;97(2):430-4. PMID: 2288551.

69. Mascia L, Zavala E, Bosma K, et al. High tidal volume is associated with the development of acute lung injury after severe brain injury: An international observational study. Crit Care Med. 2007 Aug;35(8):1815-20. PMID: 17568331.

70. Gama de Abreu M, Guldner A, Pelosi P. Spontaneous breathing activity in acute lung injury and acute respiratory distress syndrome. Curr Opin Anaesthesiol. 2012 Apr;25(2):148-55. PMID: 22227446.

71. Mascia L, Pasero D, Slutsky AS, et al. Effect of a lung protective strategy for organ donors on eligibility and availability of lungs for transplantation: A randomized controlled trial. JAMA. 2010 Dec;304(23):2620-7. PMID: 21156950.

72. Pinheiro de Oliveira R, Hetzel MP, dos Anjos Silva M, et al. Mechanical ventilation with high tidal volume induces inflammation in patients without lung disease. *Crit Care*. 2010;14(2):R39. PMID: 20236550.

73. Schultz MJ, Haitsma JJ, Slutsky AS, et al. What tidal volumes should be used in patients without acute lung injury? Anesthesiology. 2007 Jun;106(6):1226-31. PMID: 17525599.

74. Chang CH, Lee FY, Wang CC, et al. An obesity paradox of Asian body mass index after cardiac surgery: Arterial oxygenations in duration of mechanic ventilation. Scientific World Journal. 2013 Sep;2013:426097. PMID: 24163622.

75. Bojmehrani A, Bergeron-Duchesne M, Bouchard C, et al. Comparison of usual and alternative methods to measure height in mechanically ventilated patients: Potential impact on protective ventilation. Respir Care. 2014 Jul;59(7):1025-33. PMID: 24255160.

76. Tools, NHLBI ARDS Network. http://www.ardsnet.org/tools.shtml. Updated 2014. Accessed February 9, 2016.

77. Bouadma L, Mourvillier B, Deiler V, et al. A multifaceted program to prevent ventilator-associated pneumonia: Impact on compliance with preventive measures. Crit Care Med. 2010 Mar;38(3):789-96. PMID: 20068461.

78. Rello J, Lode H, Cornaglia G, et al, VAP Care Bundle Contributors. A European care bundle for prevention of ventilator-associated pneumonia. Intensive Care Med. 2010 May;36(5):773-80. PMID: 20237759.

79. Salahuddin N, Zafar A, Sukhyani L, et al. Reducing ventilator-associated pneumonia rates through a staff education programme. J Hosp Infect. 2004 Jul;57(3):223-7. PMID: 15236851.

80. Mangino JE, Peyrani P, Ford KD, et al. Development and implementation of a performance improvement project in adult intensive care units: Overview of the improving medicine through pathway assessment of critical therapy in hospital-acquired pneumonia (IMPACT-HAP) study. Crit Care. 2011;15(1):R38. PMID: 21266065.

81. Youngquist P, Carroll M, Farber M, et al. Implementing a ventilator bundle in a community hospital. Jt.Comm.J.Qual.Patient Saf. 2007 Apr;33(4):219-25. PMID: 17441560.

82. Pronovost PJ, Holzmueller CG, Martinez E, et al. A practical tool to learn from defects in patient care. Jt Comm J Qual Patient Saf. 2006 Feb;32(2):102-8. PMID: 16568924.

83. Sinuff T, Muscedere J, Cook D, et al. Canadian Critical Care Trials Group. Ventilator-associated pneumonia: Improving outcomes through guideline implementation. J Crit Care. 2008 Mar;23(1):118-25. PMID: 18359429.

84. Berenholtz SM, Hartsell TL, Pronovost PJ. Learning from defects to enhance morbidity and mortality conferences. Am J Med Qual. 2009 May-Jun;24(3):192-5. PMID: 19258468.

85. Pham JC, Colantuoni E, Dominici F, et al. The harm susceptibility model: A method to prioritise risks identified in patient safety reporting systems. Qual Saf Health Care. 2010 Oct;19(5):440-5. PMID: 20427297.

86. Tucker AL. Workarounds and resiliency on the front lines of health care. AHRQ-Patient Safety Network Web site. https://psnet.ahrq.gov/perspectives/perspective/78. Published August 2009. Updated 2009. Accessed October 2, 2015.

87. Vincent C. Understanding and responding to adverse events. N Engl J Med. 2003 Mar;348(11):1051-6. PMID: 12637617.

88. Woodward HI, Mytton OT, Lemer C, et al. What have we learned about interventions to reduce medical errors? Annu Rev Public Health. 2010;31:479-97 1 p following 497. PMID: 20070203.

89. Herzer KR, Rodriguez-Paz JM, Doyle PA, et al. A practical framework for patient care teams to prospectively identify and mitigate clinical hazards. Jt Comm J Qual Patient Saf. 2009 Feb;35(2):72-81. PMID: 19241727.

Prepared by Johns Hopkins Medicine/Armstrong Institute for Patient Safety and Quality with contract funding provided by the Agency for Healthcare Research and Quality through Contract No. HHSA2902010000271.

Disclaimer: The opinions expressed in this document are those of the authors and do not reflect the official position of AHRQ or the U.S. Department of Health and Human Services.

None of the investigators have any affiliations or financial involvement that conflicts with the material presented in this document.