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Evaluating delivery of low tidal volume ventilation in six ICUs using electronic health record data

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Abstract

Objective: Mechanical ventilation with low tidal volumes is recommended for all patients with ARDS, and may be beneficial to other intubated patients, yet consistent implementation remains difficult to obtain. Using detailed electronic health record data, we examined patterns of tidal volume administration, the effect on clinical outcomes, and alternate metrics for evaluating low tidal volume compliance in clinical practice.

Design: Observational cohort study.

Setting: Six intensive care units in a single hospital system.

Patients: Adult patients who received invasive mechanical ventilation more than 12 hours.

Intervention: none

Measurements and Main Results: Tidal volumes were analyzed across 1,905 hospitalizations. Although mean tidal volume was 6.8 mL/kg predicted body weight (PBW), 40% of patients were exposed to tidal volumes > 8 mL/kg PBW, with 11% for more than 24 hours. At a patient level, exposure to 24 total hours of tidal volumes > 8 mL/kg PBW was associated with increased mortality (odds ratio = 1.82, 95% CI 1.20 – 2.78), while mean tidal volume exposure was not (odds ratio = 0.87 per 1 mL/kg increase, 95% CI 0.74 – 1.02). Initial tidal volume settings

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Conflicts of interest

All authors report no conflicts of interest to disclose.

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strongly predicted exposure to volumes > 8 mL/kg for 24 hours, the adjusted rate was 21.5% when initial volumes were > 8 mL/kg PBW and 7.1% when initial volumes were < 8 mL/kg PBW. Across ICUs, correlation of mean tidal volume with alternative measures of low tidal volume delivery ranged from 0.38 to 0.66.

Conclusion: Despite low mean tidal volume in the cohort, a significant percentage of patients were exposed to a prolonged duration of high tidal volumes which was correlated with higher mortality. Detailed ventilator records in the electronic health record provide a unique window for evaluating low tidal volume delivery and targets for improvement.

Keywords

Mechanical Ventilation; Critical Care; Acute Respiratory Distress Syndrome; quality improvement; Critical Care Outcomes

Introduction

Invasive mechanical ventilation with low tidal volumes is the standard of care for patients with the acute respiratory distress syndrome (ARDS)(1–3) and may be beneficial to other patients receiving mechanical ventilation (4, 5). However, multiple recent studies have demonstrated that patients with ARDS do not consistently receive low tidal volume ventilation despite over 15 years of effort to ensure its adoption into clinical practice (6–9).

There remains limited understand of how best to deliver low tidal volume ventilation in clinical practice, and how best to evaluate compliance with this therapy (2, 10). One approach is to measure the mean tidal volume administered to mechanically ventilated patients in an ICU or hospital. However, focusing on the mean alone ignores the potential variation in volumes administered, nor quantifies the duration of high tidal volumes administered to individual patients, which may be more relevant to patient outcomes (11). Most studies evaluating tidal volume settings evaluate tidal volumes at one or two points during a day, lacking the granularity to precisely quantify the duration high tidal volume exposure in individual patients (6, 9, 12). With the increasing availability of detailed tidal volume documentation in electronic health records (EHR), analyzing EHR data may provide new insights into tidal volume delivery in clinical practice (7, 13, 14).

We sought to characterize patterns of tidal volume delivery by examining hourly tidal volume documentation in the EHR. We hypothesized that despite a low mean tidal volume, we would identify individual patients exposed to high tidal volumes for prolonged periods, and such exposure would be associated with worse clinical outcomes. We hypothesized that specific clinical and patient characteristics, including a patient's initial tidal volume setting, would be associated with exposure to prolonged high tidal volumes. Finally, we examined the correlation of mean tidal volume with alternate measures of low tidal volume delivery at a system-level.

Materials and Methods

This study was approved by the institutional review board at the University of Michigan. We studied hospitalizations of adult patients (age ≥ 18 years old) who received invasive mechanical ventilation for more than 12 hours in any of six intensive care units (ICU) in a large tertiary care health system in 2016. We excluded patients who received less than 12 hours of mechanical ventilation because they were not at risk for prolonged exposure to high tidal volumes. Set tidal volumes were abstracted from the EHR on volume targeted ventilator modes and observed exhaled tidal volumes were abstracted on pressure targeted ventilator modes. Because our interest was in analyzing tidal volumes primarily determined by ventilator settings rather than patient effort, we limited analysis to tidal volumes on full support modes and excluded pressure support. Further details of the tidal volume abstraction and validation process are described in the supplemental appendix.

High tidal volume exposure

Height was abstracted from the EHR to calculate tidal volumes in mL/kg predicted body weight (PBW) (3). All tidal volumes are reported in PBW throughout the manuscript. For 144 (7%) patients without a height recorded in the nursing flowsheet during the hospitalization, the most recently documented height was used if available (94 patients). The 50 patients without a height documented were excluded (2%). Patients with a height < 130 cm were excluded because the PBW equation may not apply (15).

High tidal volumes were defined as documented tidal volumes > 8 mL/kg PBW as recorded by a nurse or respiratory therapist. Duration of exposure to high tidal volumes were quantified in two ways. First, the total time patients received tidal volumes > 8 mL/kg was calculated and patients exposed for 24 hours were identified. Second, to capture the magnitude and duration of high tidal volume, we defined a new variable, *liter-hours* > 6.5 . This variable is analogous to “pack-years” when quantifying smoking history. First, 6.5 is subtracted from each tidal volume or set to 0 if the tidal volume is below 6.5. Then, each result is multiplied by the duration of time at that volume. Finally, the products are summed for each patient. For example, a tidal volume of 8.5 mL/kg PBW for 10 hours is 20 *liter-hours* > 6.5 .

Clinical variables

Demographics (age, sex, race), admission source, height, weight, and clinical variables from the first 24 hours of mechanical ventilation were collected. Clinical variables included $\text{PaO}_2/\text{FiO}_2$ or calculated $\text{SaO}_2/\text{FiO}_2$ if a PaO_2 was unavailable (16, 17), pH, PaCO_2 , lactate, serum bicarbonate, estimated dead space fraction (18), Richmond Agitation Sedation Scale (RASS) score, Sequential Organ Failure Assessment (SOFA) score, and presence of hypercarbic respiratory failure. Hypercarbic respiratory failure was defined as a pH < 7.35 and $\text{PaCO}_2 > 50$ mm Hg. Missing variables were imputed using multiple imputation (19). Chart reviews were performed on subgroup of consecutive patients with a $\text{PaO}_2/\text{FiO}_2 < 300$ for ARDS by critical care trained physicians using a previously described approach (20).

Statistical analysis—Duration of mechanical ventilation, mean tidal volume, duration of tidal volume > 8 mL/kg PBW, and tidal volume *liter-hours* > 6.5 were calculated for the entire cohort, the subgroups of patients with and without moderate to severe hypoxic respiratory failure ($\text{PaO}_2/\text{FiO}_2 < 200$) and patients reviewed for ARDS. To visualize delivered tidal volumes and transitions during mechanical ventilation, patients were grouped based on tidal volume ranges (< 6.5 mL/kg, 6.5 – 8 mL/kg, > 8 mL/kg) at 12-hour intervals and an Alluvial diagram was created (21, 22).

Multivariable logistic regression models were used to examine the association between high tidal volume and in-hospital mortality. For all models, hospital mortality was the outcome variable. The primary exposure was either the binary variable *tidal volume > 8 mL/kg for 24 hours*, the continuous variable *liter-hours > 6.5*, or the patient's *mean tidal volume*. Models were adjusted for duration of mechanical ventilation, all demographic and clinical variables above, admission location (emergency department (ED), procedural area, hospital ward, or hospital transfer), and the ICU where care was provided.

A multivariable logistic regression model was also used to examine the association between clinical variables and exposure to 24 hours of $\text{Vt} > 8 \text{ mL/kg}$. In this model, the independent variables included the first set tidal volume, all demographic and clinical variables above, admission location, and the ICU where care was provided.

For the six individual ICUs, mean tidal volume among all documented tidal volumes and four alternate measures of low tidal volume performance were calculated: 1) percentage of patients exposed to tidal volumes > 8 mL/kg PBW for 24 hours, 2) mean tidal volume among the first documented tidal volumes after ICU admission, 3) rate that tidal volumes were decreased when elevated per 100 ventilator days, and 4) rate that tidal volumes were increased when not elevated per 100 ventilator days. Further details are provided in the supplement. Spearman rho was used to quantify to correlation between measures (23).

All analysis was conducted in Stata 14 (College Station, TX) and R (R Foundation for Statistical Computing, Vienna, Austria).

Results

Tidal volumes were analyzed for 1,905 consecutive hospital admissions where patients received at least 12 hours of mechanical ventilation. The six ICUs analyzed cared for a range of 140 to 605 patients. The data included 175,332 mechanical ventilation hours and 242,019 recorded tidal volumes. The median duration of time between documented tidal volumes was 35 minutes (IQR 15 – 60).

Mean tidal volume in the cohort was 6.8 mL/kg PBW (Table 1). However, 40% of patients were exposed to tidal volumes > 8 mL/kg for a median duration of 14 hours (IQR 3–33), and 11% were exposed for more than 24 hours. Half of tidal volumes > 8 mL/kg were between 8 – 8.5 mL/kg (eFigure 1). Patients exposed to more than 24 total hours of high tidal volumes had a median of 65 (IQR 45 – 107) separate high tidal volumes recorded. Mean tidal volume was lower in patients with hypoxic respiratory failure compared to other patients (6.6 mL/kg vs 7.0 mL/kg, $p < 0.01$), and lower in patients with ARDS (6.4 mL/kg vs. 6.8 mL/kg, $p <$

0.01). However, patients with hypoxic respiratory failure and ARDS had longer duration of mechanical ventilation, were more often exposed to tidal volumes > 8 mL/kg for 24 hours, and had higher liter-hours > 6.5 (Table 1).

Exposure to tidal volumes > 8 mL/kg for 24 total hours was associated with increased hospital mortality (Table 2) in both a model adjusting for duration of mechanical ventilation (odds ratio = 1.51, 95% CI 1.08 – 2.11) and a fully adjusted model (odds ratio = 1.82, 95% CI 1.20 – 2.78). Adjusted mortality was 28.8% (95% CI 23.1% – 34.6%) in patients exposed to tidal volumes > 8 mL/kg for 24 hours compared to 20.6% (95% CI 18.9% – 22.4%) in other patients. Even exposure to > 8 mL/kg for 12 hours was also associated with increased mortality (odds ratio = 1.66, 95% CI 1.15 – 2.38). Tidal volume *liter-hours* > 6.5 was associated with mortality in adjusted analysis (odds ratio 1.11 per 50 liter-hours, 95% CI 1.05 – 1.17) while the patient's mean tidal volume was not (odds ratio = 0.87 per 1 mL/kg increase, 95% CI 0.74 – 1.02).

Transitions between tidal volumes occurred infrequently for most patients (Figure 1). When transitions occurred, they more often occurred during the first 12 hours of mechanical ventilation (19% of patients) compared to later 12-hour periods (7% on average). For patients with tidal volumes > 8 mL/kg at mechanical ventilation onset, 27% were lowered by hour 12. For patients with tidal volumes < 8 mL/kg, 3% were increased to > 8 mL/kg by hour 12.

Initial tidal volume, duration of mechanical ventilation, height, weight, RASS score, and admission from the ED or outside hospital were all independently associated with exposure to tidal volumes > 8 mL/kg for 24 hours (Table 3). In patients with an initial tidal volume above 8 mL/kg, the adjusted rate of exposure to tidal volumes > 8 mL/kg for 24 hours was 21.5% (95% CI, 17.9% – 25%) while the rate was 7.1% (95% CI, 5.8% – 8.4%) when the initial tidal volume was < 8 mL/kg.

There was substantial variation among individual ICUs in alternate measures of low tidal volume delivery (Figure 2, eTable 2). In general, ICUs with lower mean tidal volume also had a lower percentage of patients exposed to tidal volumes > 8 mL/kg for 24 hours. Yet, the ICU with the lowest average tidal volume of 6.4 mL/kg still had 7.4% of patients exposed to tidal volumes > 8 mL/kg for 24 hours. Mean tidal volume was moderately correlated with alternate measures of low tidal volume delivery (Spearman rho 0.38 to 0.67) (eTable 3).

Discussion

In this analysis, we demonstrate how electronic health record data can be used to evaluate delivery of low tidal volume ventilation in clinical practice and provide novel alternate metrics for improvement. Despite seemingly acceptable mean tidal volume of 6.8 mL/kg PBW, 11% of patients were exposed to tidal volumes > 8 mL/kg for 24 hours, which was associated with increased mortality. Assessing mean tidal volume alone did not provide a complete picture of compliance with low tidal volume ventilation, nor was mean tidal volume correlated with hospital mortality at a patient level. Across ICUs, mean tidal volume

was only moderately correlated with alternate EHR derived measures of low tidal volume delivery, which may offer additional targets for improvement in clinical practice.

While many previous studies have described inadequate delivery of low tidal volume ventilation, the current study was uniquely able to quantify delivered tidal volumes using EHR data and uncover significant deviations in individual patients. The cohort's mean tidal volume of 6.8 mL/kg was significantly lower than reported in the recent PROVENT study (7.9 mL/kg PBW) (24), or LUNG-SAFE study (7.6 mL/kg PBW) (6), yet, 1 in 10 patients in the cohort still received tidal volumes > 8 mL/kg for 24 hours. At the institution where this study was performed, mean tidal volume is regularly audited and reported to respiratory therapy staff and ICU directors, and has steadily declined between 2006 to 2016. Our study results highlight the inadequacy of mean tidal volume as the sole measure for evaluating low tidal volume delivery. Auditing and providing feedback on these alternate measures will be an important aspect of any quality improvement initiative moving forward (2).

The current study provides additional empirical support for default low tidal volume settings as a strategy for ensuring low tidal volume ventilation throughout mechanical ventilation (25, 26). Adjusted rates of exposure to 24 hours of high tidal volumes were three time higher when initial tidal volumes were above 8 mL/kg PBW compared to below 8 mL/kg PBW. As most tidal volume changes occurred in the first 12 hours of a ventilator episode, this appears to be a critical window for ensuring patients are placed on low settings if they are initially elevated.

Other factors associated with high tidal volumes included shorter stature, a finding previously described in ARDS patients (27). Patients presenting from the ED were also more likely to receive higher tidal volumes, consistent with previous findings (9), but the reason why ED patients are more likely to receive high tidal volumes remain unknown and warrants further study. Clinical factors that might lead a clinician to intentionally set tidal volumes higher (e.g. metabolic acidosis, hypercarbic respiratory failure) were not associated with high tidal volume administration, in contrast to previous research (27–29).

At our institution, the EHR automatically calculates predicted body weight in the respiratory flowsheet when height is recorded in the nursing flowsheet during the hospitalization. However, 7% of patients did not have a height recorded, preventing this automatic calculation. Additionally, 2% of patients were excluded from analysis because they lacked any height documentation in the EHR, preventing a predicted body weight calculation and also potentially limiting accurate dosing of certain medications—another opportunity for improvement.

Critical to ensuring adoption of any evidenced-based intervention is the ability to identify and measure the core components of the intervention, evaluate the success of an implementation strategy to improve adoption, and evaluate sustained use (30). For low tidal volume ventilation, detailed EHR data offers a unique window to better dissect its delivery in clinical practice, identify targets for improvement, and design more informed implementation strategies. The percentage of patients exposed to 24 hours of high tidal volumes is potentially more patient-centered because of its association with clinical

outcomes. It also inherently identifies a specific group of patients that can be reviewed to inform targeted strategies for improvement. Other measures that may serve as concrete targets include the rate that high tidal volumes were lowered on days they were elevated or the rate that low tidal volumes were increased.

This study is consistent with others showing that low tidal volumes is beneficial in all patients receiving mechanical ventilation, and not just ARDS (4, 5, 12). Because the current study was observational, it is not proof of a causal relationship and could be biased by unmeasured confounding. However, the effect was unchanged after adjusting for severity of illness, in contrast to many confounded relationships where effect estimates decrease with improved risk adjustment (31). Additional randomized trials of differing implementation strategies, timing of tidal volume reviews and feedback, and/or nudges might be useful for confirming these results (2).

The current study has additional limitations. The analysis was performed at a single tertiary care center which may limit generalizability. However, it included six diverse ICUs (medical, surgical, cardiac, trauma, neurologic, and cardiovascular surgery), with different nursing, respiratory staff, and physicians from different subspecialties. The variation identified across ICUs provided some assurance that the findings are robust. Despite effort to clean and validate EHR data, some errors may remain; if differential, these could introduce bias to some analyses. Because of sparse documentation, ventilator pressures (i.e. plateau pressures, driving pressures) were not evaluated despite their importance in lung protective ventilation, nor could ventilator dyssynchrony be quantified. Peak pressure or the difference between set and observed tidal volume may serve as reasonable surrogates for these variables but warrant further study. Direct analysis of the ventilator waveform data could also provide even more detail of ventilator management if such data is available (32).

Conclusions

Measuring mean tidal volume alone provided an incomplete picture of low tidal volume ventilation delivery in clinical practice. Future efforts to improve fidelity with low tidal volume ventilation may benefit from examining detailed tidal volume administration records within the EHR, which can provide an accurate assessment of compliance while informing strategies for improvement.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Tidal volume settings and transitions over the first 48 hours of mechanical ventilation. Patients are categorized at 12-hour intervals as receiving tidal volumes in one of four groups: < 6.5 mL/kg predicted body weight (PBW), 6.5 – 8 mL/kg PBW, > 8 mL/kg PBW, or not intubated. This figure demonstrates that the majority of patients remained in the same tidal volume category over their episode of mechanical ventilation, and transitions between tidal volumes, while infrequent, occurred most often between hour 0 and 12.

Alternative measures of low tidal volume delivery						
	Mean Vt (mL/kg)	Initial Vt (mL/kg)	Vt > 8 mL/kg 24 hours (%)	Vt not decreased when > 8 mL/kg (per 100 vent-days)	Vt increased when < 8 mL/kg (per 100 vent-days)	
ICU A	6.38	6.58	7.4	68	4	Lowest
ICU B	6.49	7.03	10.3	69	3	
ICU C	6.50	7.00	8.4	68	8	
ICU D	6.86	7.17	8.9	79	1	
ICU E	6.88	6.94	9.3	74	4	
ICU F	7.44	7.82	19.9	73	11	Highest

Figure 2.

Individual ICU performance on mean tidal volume (Vt) and alternate measures of low tidal volume delivery. All tidal volumes are in mL/kg predicted body weight. Alternate measures include: initial Vt: mean of first recorded tidal volumes after ICU admission for each patient; >24 hrs (Vt > 8 mL/kg 24 hours): percentage of patients exposed to Vt > 8 mL/kg for 24 hours; Not decreased (Vt not decreased when > 8 mL/kg): rate that Vt was not lowered to < 8 mL/kg on a ventilator day when above > 8 mL/kg; Increased (Vt increased when < 8 mL/kg): rate that Vt was increased to > 8 mL/kg on a ventilator day when Vt < 8 mL/kg. Rates of changing tidal volume are per 100 ventilator-days. Further details of rate calculations provided in the supplement.

Table 1.

Mechanical ventilation duration, mean tidal volume, and high tidal volume exposure (>8 mL/kg predicted body weight)

Result	Hypoxic respiratory failure			Reviewed for ARDS	
	All (n = 1905)	P/F > 200 (n = 828)	P/F < 200 (n = 1077)	No ARDS (n = 236)	ARDS (n = 148)
Duration of MV, hrs Median (IQR)	56 (24–148)	42 (20–109)	72 (30–180)	51 (26–120)	153 (57–276)
Vt,mL/kg PBW, Mean [SD]	6.8 [1.7]	7 [1.6]	6.6 [1.7]	6.8 [1.5]	6.4 [1.4]
Any Vt > 8 mL/kg, %	40	34	44	33.0	53
Vt > 8 mL/kg for 24 hrs, %	11	9	13	6	13
Vt time > 8 mL/kg, hrs Median (IQR) ^a	12 (3–29)	12 (3–26)	13 (3–32)	9 (2–18)	10 (2–24)
Liter-hours > 6.5 Median (IQR) ^b	18 (3–51)	16 (4–43)	20 (2–59)	13 (1–42)	27 (2–97)

P/F, PaO₂/FiO₂; Vt, tidal volume in mL/kg predicted body weight; MV, Mechanical ventilation; hrs, hours; SD, standard deviation

^a Among patients exposed to tidal volumes > 8 mL/kg PBW at any point

^b liter-hours > 6.5 mL/kg PBW (analogous to pack-years), see text for description

Table 2.

Association between tidal volume and in-hospital mortality

Tidal volume exposure	Multivariable adjustment	
	MV duration ^a Odds ratio (95% CI)	Fully adjusted ^b Odds ratio (95% CI)
> 8 mL/kg for 24 hours	1.51 (1.08–2.11)	1.82 (1.20–2.78)
> 8 mL/kg for 12 hours	1.34 (1.02–1.75)	1.66 (1.15–2.38)
Tidal volume <i>liter-hours</i> > 6.5 ^c (per 50)		1.11 (1.05–1.17)
Mean tidal volume (per 1 mL/kg increase)		0.87 (0.74–1.02)

MV, mechanical ventilation; tidal volumes (Vt) are in mL/kg predicted body weight

^aMultivariable logistic regression only adjusted for mechanical ventilation duration^bMultivariable logistic regression adjusted for age, sex, race, mechanical ventilation duration, height, weight, clinical variables during the first 24 hours of mechanical ventilation: presence of hypercarbic respiratory failure, highest SOFA score, highest lactate, lowest PaO₂/FiO₂ ratio, lowest pH, lowest serum bicarbonate, highest dead space fraction, maximum RASS score, ICU admission location, and initial ICU where care was provided^c*liter-hours* > 6.5 mL/kg PBW (analogous to pack-years), see text for description

Table 3.

Factors independently associated with exposure tidal volume above 8 mL/kg predicted body weight for 24 hours

	Odds Ratio ^a	95% CI	p-value
Initial Vt > 8 mL/kg	5.01	3.45 – 7.28	<0.01
MV length (days)	1.10	1.08 – 1.12	<0.01
Demographics			
Age (per 10 years)	0.91	0.82 – 1.02	0.10
Female	0.66	0.42 – 1.05	0.08
Caucasian	1.23	0.77 – 1.97	0.40
Anthropometrics			
Actual height (per 10 cm)	0.42	0.33 – 0.53	<0.01
Actual weight (per 10 kg)	1.13	1.06 – 1.21	<0.01
Clinical variables, first 24 hours of MV ^b			
Hypercarbic respiratory failure ^c	1.08	0.67 – 1.73	0.76
Highest SOFA score	1.02	0.96 – 1.08	0.53
Highest Lactate, mmol/L	1.04	0.99 – 1.09	0.12
Lowest PaO ₂ /FiO ₂			
> 300	Reference		
200–300	0.49	0.27 – 0.88	0.02
100–200	0.91	0.53 – 1.58	0.74
< 100	0.66	0.34 – 1.3	0.23
Lowest pH			
> 7.35	Reference		
7.2–7.35	1.05	0.66 – 1.67	0.83
< 7.2	1.07	0.55 – 2.08	0.84
Lowest Serum HCO ₃ , mEq/L			
> 26	Reference		
22–26	1.26	0.72 – 2.19	0.42
< 22	1.54	0.82 – 2.87	0.18
Highest dead space fraction	2.83	0.49 – 16.17	0.24
Highest RASS score	1.11	1.02 – 1.21	0.02
Admission location			
General Ward	Reference		
Procedure	1.07	0.47 – 2.43	0.88
Emergency Department	2.22	1.24 – 3.97	0.01
Transfer	2.05	1.11 – 3.8	0.02

Vt, Tidal volume in mL/kg predicted body weight; MV, Mechanical ventilation; HCO₃, bicarbonate; RASS, Richmond Agitation Sedation Scale; SOFA, Sequential Organ Failure Assessment

^a Multivariable logistic regression model adjusted for all listed variables and the primary ICU where care was provided.

^b Clinical variables are the worst values during first 24 hours of mechanical ventilation, missing variables imputed using multiple imputation.

^CHypercarbic respiratory failure: pH < 7.35 and PaCO₂ > 50.

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