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Variability in usual care mechanical ventilation for pediatric acute lung injury: the potential benefit of a lung protective computer protocol

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Abstract *Purpose:* Although pediatric intensivists claim to embrace lung protective ventilation for acute lung injury (ALI), ventilator management is variable. We describe ventilator changes clinicians made for children with hypoxemic respiratory failure, and evaluate the potential acceptability of a pediatric ventilation protocol. *Methods:* This was a retrospective cohort study performed in a tertiary care pediatric intensive care unit (PICU). The study period was from January 2000 to July 2007. We included mechanically ventilated children with PaO_2/FiO_2 (P/F) ratio less than 300. We assessed variability in ventilator management by evaluating actual changes to ventilator settings after an arterial blood gas (ABG). We evaluated the potential acceptability of a pediatric mechanical ventilation protocol we adapted from National Institutes of Health/National Heart, Lung, and Blood Institute (NIH/NHLBI) Acute Respiratory Distress Syndrome (ARDS) Network protocols by comparing actual practice changes in ventilator settings to changes that would have been recommended by the protocol. *Results:* A total of 2,719 ABGs from 402 patients were associated with 6,017 ventilator settings. Clinicians infrequently decreased FiO_2, even when the PaO_2 was high (>68 mmHg). The protocol would have recommended more positive end expiratory pressure (PEEP) than was used in actual practice 42% of the time in the mid PaO_2 range (55–68 mmHg) and 67% of the time in the low PaO_2 range (<55 mmHg). Clinicians often made no change to either peak inspiratory pressure (PIP) or ventilator rate (VR) when the protocol would have recommended a change, even when the pH was greater than 7.45 with PIP at least 35 cmH_2O. *Conclusions:* There may be lost opportunities to minimize potentially injurious ventilator settings for children with ALI. A reproducible pediatric mechanical ventilation protocol could prompt clinicians to make ventilator changes that are consistent with lung protective ventilation.

Keywords Acute lung injury · Clinical protocols · Decision support systems · Pediatrics · Critical care

Introduction

Ventilator management for children with hypoxemic respiratory failure, acute lung injury (ALI), and acute respiratory distress syndrome (ARDS) is variable [1]. Adult intensivists have generally accepted National Institutes of Health/National Heart, Lung, and Blood Institute (NIH/NHLBI) Acute Respiratory Distress Syndrome (ARDS) Network ventilator protocols [2] which have improved outcomes for adults with ALI/ARDS [2–5], but protocol implementation is not yet widespread [6–8]. Few ventilator protocols exist for pediatric critical care, although studies of ALI in children [9, 10] have used protocols described as similar to published ARDS Network protocols [2].

However, protocols developed in the adult intensive care unit (ICU) may need modification to match pediatric ICU (PICU) needs. For mechanical ventilation, pediatric intensivists commonly use different modes of ventilation than adult intensivists. There are unanswered questions regarding the weight to use for tidal volume targets, where and how to measure tidal volume, the magnitude of changes to fraction of inspired oxygen (FiO_2), and the acceptable range of permissive hypercapnia [11]. Given these potential differences, we modified the ARDS Network protocol tables to develop a pediatric ALI/ARDS mechanical ventilation protocol [12].

We sought to describe usual care clinician decisions for mechanically ventilated children with ALI/ARDS, and to determine the potential applicability of our pediatric mechanical ventilation protocol. We extracted mechanical ventilation, oxygenation, and blood gas data from a PICU database that contained 7 years of information. We compared these historical clinician-determined ventilator settings with recommendations that would have been generated by the protocol.

Our clinicians agreed to use a lung protective mechanical ventilation strategy. Nevertheless, we expected variability in usual care ventilator management for children with lung injury, and inconsistency in lung protective decisions.

Methods

The Children's Hospital Los Angeles Institutional Review Board approved this study. Patients were eligible if they were endotracheally intubated and mechanically ventilated, and had at least one PaO_2/FiO_2 (P/F) ratio less than 300 within 24 h of intubation. Patients were excluded if they had heart failure, uncorrected cyanotic heart disease, or primary pulmonary hypertension. All patients met three of the four diagnostic criteria for ALI (acute onset of disease, P/F ratio <300, and no left ventricular dysfunction). The fourth criterion for ALI is bilateral infiltrates; we used chest radiograph information regarding infiltrates for subgroup analysis.

We examined data from January 2000 through July 2007. The reported benefits of lung protective ventilation in adults [13, 14] just prior to 2000 affected our clinical practice. During the study period, our clinicians agreed with principles of lung protective ventilation strategies, although we had no formal mechanical ventilation protocol. We sought to use pressure-limited modes of ventilation, with target peak inspiratory pressure (PIP) less than 35 cmH_2O, ventilator rate (VR) less than 35 bpm, and allowed permissive hypercapnia. We sought to adjust positive end expiratory pressure (PEEP) and FiO_2 to maintain SpO_2 between 88 and 95% or PaO_2 greater than 60 mmHg. We did not commonly employ recruitment maneuvers [15]. We used three conventional ventilators: Servo 300 (Siemens, Solna, Sweden), Avea (Viasys Healthcare, Yorba Linda, CA, USA), and Servo i (Maquet Medical, Solna, Sweden).

Data extraction

We extracted data from the electronic healthcare record and from two local computer databases (Philips CareVue ISM and Microsoft Access®). The local databases are routinely evaluated for accuracy, and have been determined to be appropriate for clinical care, quality improvement, and research. An attending pediatric radiologist read all chest X-rays, and we reviewed those reports for diagnostic criteria for ALI.

The first P/F ratio less than 300 after intubation defined the beginning of the study for each patient. We extracted all blood gas values and ventilator settings beginning at or immediately prior to this, and moved forward for 3 days or until extubation (whichever was first). We associated ventilator settings with blood gas values on the basis of time stamps. We determined actual clinical care changes to ventilator settings by comparing pairs of sequential ventilator settings before and after the arterial blood gas (ABG) if the time stamps for the settings were no more than 8 h apart. We used all intubation and extubation times to calculate 28-day ventilator-free days (VFDs). We limited analysis to patients supported with pressure control (PC) ventilation (>90% of patients).

Pediatric ALI/ARDS mechanical ventilation protocol

Our pediatric ALI/ARDS mechanical ventilation protocol was modified from ARDS Network protocol tables [2] using preliminary data and expert review by clinicians from the Pediatric Acute Lung Injury and Sepsis Investigators (PALISI) Network and the NICHD Collaborative Pediatric Critical Care Research Network (CPCCRN). We believe it represents the best available evidence and current consensus of pediatric critical care clinicians. The impact of this protocol on clinical outcomes still needs to

be evaluated, but was not an objective of our current study.

The protocol contains decision tables that implement lung protective ventilation strategies through discrete, explicit steps. Oxygenation tables evaluate combinations of PEEP and FiO_2 stratified into high PaO_2 (>68 mmHg), mid PaO_2 (55–68 mmHg), and low PaO_2 (<55 mmHg) subsets. The adult protocol table bins are based on FiO_2 increments of 0.1; this was reduced to 0.05 for the pediatric protocol.

Ventilation tables describe combinations of ventilator support, stratified by pH, for four different modes of ventilation [PC, volume control (VC), pressure-regulated volume control (PRVC), and high frequency oscillatory ventilation (HFOV)]. We retained pH ranges from the adult protocol. For the PC mode of ventilation, used in this study, pH categories are combined with three ranges of PIP (≤28, 29–35, and >35 cmH_2O), and when pH is less than 7.3, additional stratification is based on VR (breaths per minute, bpm). Pediatric clinicians recommended 25 bpm as a stratification point (compared to 35 bpm in the ARDS Network protocol) because they felt pressure support is frequently added to controlled modes of ventilation in pediatrics, as opposed to pure assist control modes (Table 4).

Data preparation: use of the mechanical ventilation protocol

We used the pediatric mechanical ventilation protocol to group data for analysis. Our protocol tables specify combinations of blood gas and ventilator data ranges and define data bins. Each data bin contains a treatment recommendation. We grouped the usual clinical care data in the same data bins. We entered the actual clinical ABG values and ventilator settings from the database into a computer version of the pediatric ventilator protocol to determine what the protocol would have recommended for changes to PEEP, FiO_2, PIP, and VR. We compared the computer protocol recommendations to the actual clinical care changes recorded in the database.

Analysis

We used descriptive statistics for blood gas and ventilator settings. To examine variability of usual care regarding oxygenation, we created a box plot of FiO_2, stratified by PEEP (Fig. 2a). To evaluate variability in ventilation, we calculated the frequency of changes to either PIP or VR after an ABG for each data bin in the ventilation table (Tables 4, 5).

To examine potential applicability of the pediatric mechanical ventilation protocol, we assessed percent agreement between clinical care changes in PEEP and FiO_2 after an ABG and those that would have been recommended by the protocol (Table 3). We also calculated the concordance of actual clinical care with the protocol recommendation for each of the 18 ventilation bins (Tables 4, 5).

All patients met at least three of four criteria for ALI. We performed subgroup analyses on patients with

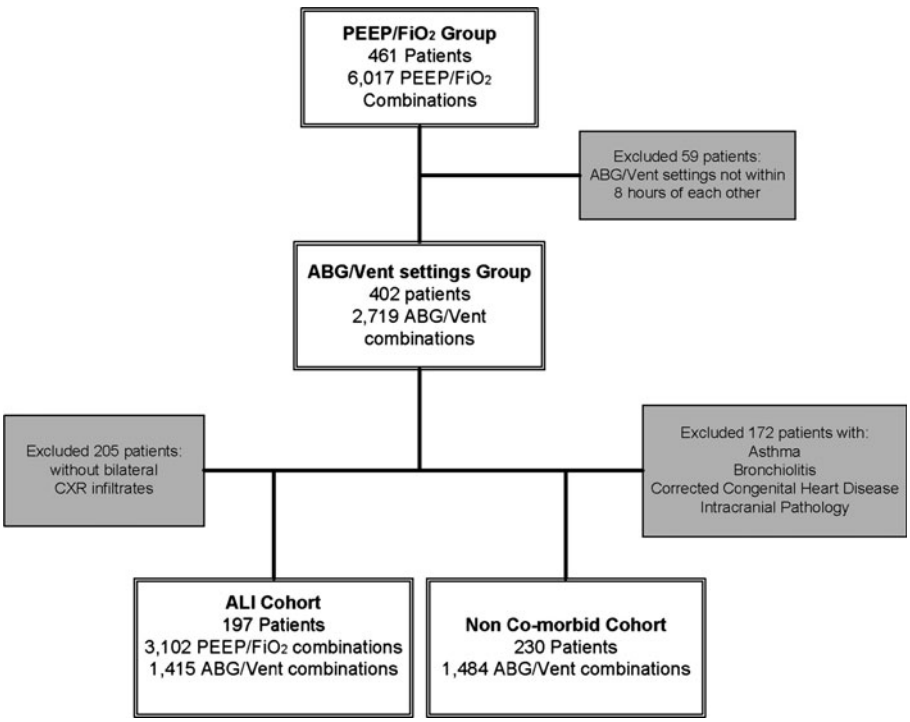

Fig. 1 Flow diagram detailing the number of patients and observations of ABG and ventilator settings for the entire cohort of children, as well as the two subgroups of children with bilateral pulmonary infiltrates on chest X-ray (ALI cohort) and those without co-morbidities that may affect ventilator management (non co-morbid cohort)

bilateral pulmonary infiltrates (ALI cohort, Table ESM 1a; Table 4b, Fig. 2b), thus meeting all four ALI criteria. We also performed subgroup analyses on patients free from specific co-morbidities that may affect ventilator management (non co-morbid cohort, Table ESM 1b, Table ESM 2). The specific co-morbidities excluded were diseases that may elevate airway resistance and make physicians reluctant to increase PEEP (asthma, bronchiolitis); patients at risk of pulmonary hypertension, where higher PaO_2 and pH may be preferred (history of congenital heart disease or secondary pulmonary hypertension); or those with diagnoses that predispose them to intracranial hypertension (head trauma, hydrocephalus, intracranial tumor). We believe the non co-morbid cohort consists of patients more likely to be managed with a lung protective strategy. We compared the percent agreement between actual clinical care and computer protocol recommendations for these subgroups to the entire cohort using Yates' corrected chi-squared tests to determine if the subgroups differed from the overall group.

Table 1 Demographics and outcomes of included patients

Variable	Count (%) or median (IQR) $N = 402$
Gender (male)	227 (56.5)
Age (years)	4.5 (1.0, 12)
Weight (kg)	16 (9, 36)
Race	
White	70 (17.4)
Latino	194 (48.3)
Black	48 (11.9)
Other	90 (22.4)
Primary diagnosis	
Pulmonary	138 (34.3)
Cardiovascular	41 (10.2)
Shock/sepsis	45 (11.2)
Neurologic	46 (11.5)
Metabolic/renal	20 (5.0)
Other	27 (6.7)
GI	56 (13.9)
Ortho/trauma	29 (7.2)
Any diagnosis	
Chronic lung disease	34 (8.5)
Asthma or bronchiolitis	29 (7.2)
Congenital heart disease (corrected or non-cyanotic)	59 (14.7)
Pulmonary HTN (acquired)	18 (4.5)
Risk of intracranial HTN	69 (17.2)
Immune compromised	95 (23.6)
Pneumonia	85 (21.1)
Shock/sepsis	109 (27.1)
Bilateral pulmonary infiltrates	197 (49)
P/F ratio	140 (85, 192)
Inotropes/vasopressors	184 (45.8)
Mortality (died)	98 (24.4)
28-day vent-free days	15.4 (0, 23.3)
Length of stay (days)	10 (5, 17)

Results

We analyzed 6,017 ventilator settings from 461 patients, and were able to associate ventilator settings with 2,719 ABG values from 402 patients (Fig. 1; Table 1). The median P/F ratio was 140. Overall mortality was 24.4%; the median value of 28-day VFDs was 15.4 (Table 1). The median interval between ventilator changes was ~4 h, with a PEEP of 8 cmH_2O and tidal volume of 7.4 ml/kg (Table 2). Peak inspiratory pressure was no greater than 35 cmH_2O in 90% of observations, and 98% were no greater than 40 cmH_2O. Median VR was 20 bpm and 75% of values were less than 25 bpm (Table 2).

Nearly half of the patients had bilateral pulmonary infiltrates (meeting all four ALI criteria), accounting for 3,102 of the 6,017 PEEP/FiO_2 combinations and 1,415 of the 2,710 ABG/vent setting combinations (Fig. 1). These patients were analyzed as the ALI cohort.

A total of 172 of the 402 patients had one or more of the specified co-morbidities. The remaining 230 patients were analyzed as the non co-morbid cohort, with 1,484 ABG/vent setting combinations (Fig. 1).

Changes in FiO_2 and PEEP

Clinicians changed FiO_2 34% (2,023/6,017) of the time. The most common FiO_2 step size was 0.05, followed by 0.1, for both decreases and increases in FiO_2 (Fig. ESM 1). Clinicians changed PEEP only 14% of the time (803/6,017). The most common changes were an increase or decrease of 2 cmH_2O (60% of all PEEP changes). There was considerable variability in the amount of FiO_2 used across different levels of PEEP (Fig. 2a). Overall, clinicians generally used higher FiO_2 and less PEEP than the protocol would have recommended, particularly when FiO_2 exceeded 0.7 (Fig. 2a).

Comparisons between actual clinical care changes to ventilator settings and protocol recommendations for the

Table 2 Descriptive statistics from the 2,719 ventilator settings and blood gas pairs, generated from the 402 children

Variable	Median (IQR) $N = 2,719$
Time between ventilator settings (h)	4.01 (3.17, 4.83)
pH	7.38 (7.32, 7.44)
$PaCO_2$ (mmHg)	43 (37, 50)
PaO_2 (mmHg)	91 (71, 125)
Ventilator rate (bpm)	20 (16, 25)
FiO_2	0.45 (0.40, 0.60)
PEEP (cmH_2O)	8 (6, 10)
PIP (cmH_2O)	28 (24, 32)
V_T (ml/kg)[a]	7.4 (5.9, 9.2)

[a] Exhaled tidal volume measured at the ventilator with appropriate compensation for tubing compliance. This value was then divided by actual body weight to report tidal volume (V_T, ml/kg)

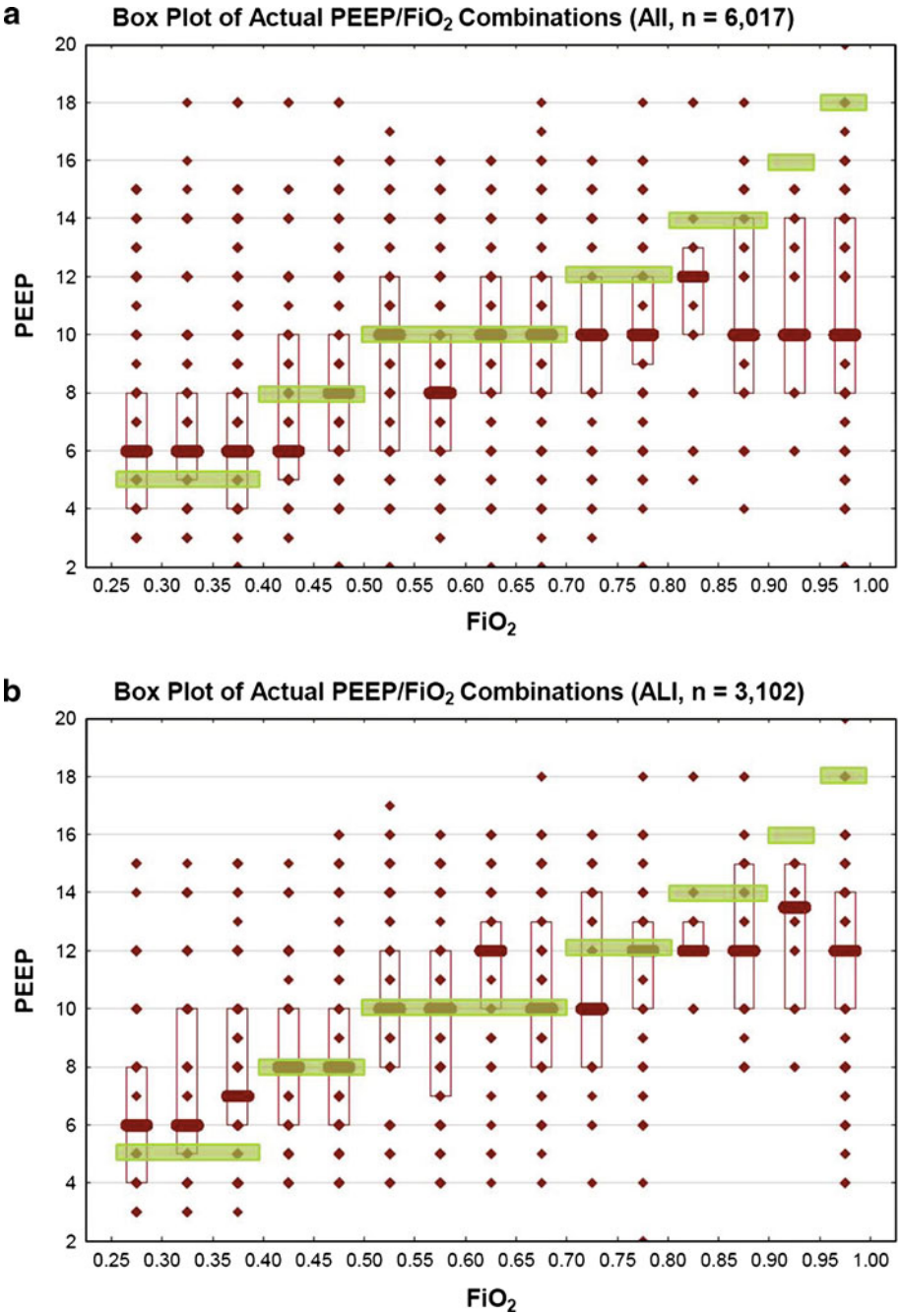

Fig. 2 PEEP/FiO_2 titration tables from clinical care for all patients (**a**) and for patients with bilateral pulmonary infiltrates (ALI cohort, **b**). The *y*-axis represents actual PEEP values as a function of actual FiO_2 used (*x*-axis). The superimposed *green boxes* represent the pediatric mechanical ventilation protocol target combinations of FiO_2/PEEP. For all patients, there is variability in FiO_2/PEEP combinations clinicians choose. In general, clinicians use less PEEP than the protocol would recommend, particularly when FiO_2 climbs above 0.7. For the ALI cohort (**b**), clinicians may be more likely to increase PEEP, although they still use less PEEP than the protocol would recommend, particularly when FiO_2 climbs above 0.8. Actual value (*diamond*), median (*bar*), IQR (*box*), protocol target (*green boxes*)

same state are shown in Table 3. In the high PaO_2 range (>68 mmHg, 77.5% of observations) and mid PaO_2 range (55–68 mmHg, 15.8% of observations), clinicians generally used higher levels of FiO_2 than the protocol would recommend. In the high PaO_2 range, there were many situations when clinicians also did not decrease PEEP when the protocol would have recommended it. In the mid PaO_2 range and low PaO_2 range (<55 mmHg, 6.7% of observations), clinicians commonly used lower levels of PEEP than the protocol would have recommended.

ALI cohort

The findings of the subgroup analyses for the ALI cohort were similar to those for the entire group. There was still variability in the amount of FiO_2 used across different levels of PEEP (Fig. 2b). It appears graphically that clinicians were more likely to increase PEEP for patients with bilateral infiltrates on chest X-ray, although they still used less PEEP than the protocol would have recommended, particularly when FiO_2 climbed above 0.8

Table 3 Clinical care changes to FiO_2 and PEEP which clinicians made in response to an arterial blood gas (clinician) compared to the changes that would have been recommended by the pediatric mechanical ventilation protocol (protocol)

Entire cohort *n* observations 2,719 (100%)	High PaO_2 (>68 mmHg) 2,108 (77.5%)	Mid PaO_2 (55–68 mmHg) 429 (15.8%)	Low PaO_2 (<55 mmHg) 182 (6.7%)
PaO_2 median (IQR)	104 (83, 136)	62 (59, 66)	47 (40, 51)
FiO_2 changes			
Clinician FiO_2 = protocol FiO_2	631 (29.9%)	128 (29.8%)	87 (47.8%)
Clinician FiO_2 < protocol FiO_2	407 (19.3%)	138 (32.2%)	38 (20.9%)
Clinician FiO_2 > protocol FiO_2	1,070 (50.8%)	163 (38%)	57 (31.3%)
PEEP changes			
Clinician PEEP = protocol PEEP	1,237 (58.7%)	164 (38.2%)	44 (24.2%)
Clinician PEEP < protocol PEEP	90 (4.3%)	182 (42.4%)	122 (67%)
Clinician PEEP > protocol PEEP	781 (37%)	83 (19.3%)	16 (8.8%)

Changes to FiO_2 and PEEP are grouped by PaO_2. Data are reported as the number and percentage of observations within each PaO_2 range in which clinician choices for FiO_2 and PEEP were less than, in line with, or greater than the protocol's recommendations

(Fig. 2b). Across all three oxygenation tables, the concordance between actual practice changes to FiO_2 and the recommendations of the ventilator protocol for the ALI cohort was similar to that for the entire group ($p > 0.05$, Table ESM 1a). Changes to PEEP were similar between groups for the mid and low PaO_2 ranges ($p > 0.15$, Table ESM 1a). There was less agreement in PEEP changes in the high PaO_2 range (4% reduction in concordance, $p = 0.001$, Table ESM 1a).

Non co-morbid cohort

In the low and mid PaO_2 ranges, the concordance between actual practice changes to FiO_2 and PEEP and the recommendations of the ventilator protocol for the non co-morbid cohort was similar to that for the entire group ($p > 0.05$, Table ESM 1b). In the high PaO_2 range, the subgroup had slightly higher agreement between actual practice and protocol recommendations for FiO_2 changes (3.4% increase in concordance, $p = 0.05$, Table ESM 1b) and slightly less agreement for PEEP changes (5% decrease in concordance, $p = 0.008$, Table ESM 1b).

Changes in PIP and ventilator rate

We used the structure of the PC ventilation table from the protocol to categorize the changes that clinicians made to VR and PIP in response to a blood gas (Table 4a). There was a median of 59 (IQR 13, 146) observations per cell. Clinician response variability existed within each cell, with clinicians most commonly making no change to either PIP or VR (median 45%; IQR 37.1, 53.4) (Tables 4a, 5). This was even true when the PIP was greater than 35 cmH_2O and the pH was greater than 7.45 (36%), or the PIP was greater than 35 cmH_2O and the pH was between 7.30 and 7.45 (53%). Excluding three cells where the protocol would recommend no change to PIP or VR, or had a combination recommendation (decrease PIP and increase VR), clinicians made changes similar to protocol recommendations a median 42% (IQR 37.7, 49.8%) of the time, and opposite to the protocol's recommendation a median of 11.1% (IQR 7.7, 17.9%) of the time.

ALI cohort

For the 1,415 ABG/vent setting combinations in the ALI cohort 7 cells had fewer than 10 observations, and were excluded from analysis. The responses in each of the included cells were nearly identical to the responses for the entire cohort (Table 4b).

Non co-morbid cohort

For the 1,484 ABG/vent setting combinations from the non co-morbid cohort, 5 cells had fewer than 10 observations, and were excluded. The responses in each of the included cells were similar to those for the entire cohort (Table ESM 2).

Discussion

This analysis demonstrates that clinicians behave inconsistently in their decisions to change ventilator support for children with hypoxemic respiratory failure or ALI. During this study period, the pediatric practitioners in our unit claimed to embrace the general tenets of lung protective pressure control ventilation; however, changes in ventilator settings were variable for similar patient states. Most notably, clinicians did not decrease FiO_2 when the PaO_2 was in a high range. Clinicians used low levels of PEEP and high levels of FiO_2 when PaO_2 was in the low range. High peak pressures and ventilator rates were frequently not decreased, even when the pH was greater

Table 4 Adapted ventilation table for PC mode, with cell numbers listed in the lower left hand corner of each cell (corresponding to Table 5)

a

PIP / pH	≤ 28 cm H_2O	28-35 cm H_2O	> 35 cm H_2O
>7.45	Dec. PIP by 2 cm H_2O Dec. VR by 20% 1	Dec. PIP by 2 cm H_2O 7	Dec. PIP by 4 cm H_2O 13
7.30-7.45	Dec PIP by 2 cm H_2O 2	Dec. PIP by 2 cm H_2O 8	Dec. PIP by 2 cm H_2O 14
7.15-7.30 VR <25	Inc. PIP by 2 cm H_2O Inc. VR by 20% 3	No change to PIP Inc. VR by 20% 9	Dec. PIP by 2 cm H_2O Inc. VR by 20% 5
7.15-7.30 VR ≥ 25	Inc. PIP by 4 cm H_2O 4	No change to PIP or VR Consider $NaHCO_3$ if PCO_2 < 25 10	Dec. PIP by 2 cm H_2O Consider $NaHCO_3$ if PCO_2 < 25 16
< 7.15 VR < 25	Inc. PIP by 4 cm H_2O Inc. VR by 20% 5	Inc. PIP by 2 cm H_2O Inc. VR by 20% 11	Inc. VR by 20% Consider $NaHCO_3$ if PCO_2 < 25 17
< 7.15 VR ≥ 25	Inc. PIP by 4 cm H_2O Consider $NaHCO_3$ if PCO_2 < 25 6	Inc. PIP by 2 cm H_2O Consider $NaHCO_3$ if PCO_2 < 25 12	No change to PIP or VR Consider $NaHCO_3$ if PCO_2 < 25 18

Legend (% agreement of clinical care with protocol recommendation)

> 50% agreement	40 to 50% agreement	30 to <40% agreement	< 30% agreement	< 10 Observations

b

PIP / pH	≤ 28 cm H_2O	28-35 cm H_2O	> 35 cm H_2O
>7.45	Dec. PIP by 2 cm H_2O Dec. VR by 20% 1	Dec. PIP by 2 cm H_2O 7	Dec. PIP by 4 cm H_2O 13
7.30-7.45	Dec PIP by 2 cm H_2O 2	Dec. PIP by 2 cm H_2O 8	Dec. PIP by 2 cm H_2O 14
7.15-7.30 VR <25	Inc. PIP by 2 cm H_2O Inc. VR by 20% 3	No change to PIP Inc. VR by 20% 9	Dec. PIP by 2 cm H_2O Inc. VR by 20% 15
7.15-7.30 VR ≥ 25	Inc. PIP by 4 cm H_2O 4	No change to PIP or VR Consider $NaHCO_3$ if PCO_2 < 25 10	Dec. PIP by 2 cm H_2O Consider $NaHCO_3$ if PCO_2 < 25 16
< 7.15 VR < 25	Inc. PIP by 4 cm H_2O Inc. VR by 20% 5	Inc. PIP by 2 cm H_2O Inc. VR by 20% 11	Inc. VR by 20% Consider $NaHCO_3$ if PCO_2 < 25 17
< 7.15 VR ≥ 25	Inc. PIP by 4 cm H_2O Consider $NaHCO_3$ if PCO_2 < 25 6	Inc. PIP by 2 cm H_2O Consider $NaHCO_3$ if PCO_2 < 25 12	No change to PIP or VR Consider $NaHCO_3$ if PCO_2 < 25 18

Legend (% agreement of clinical care with protocol recommendation)

> 50% agreement	40 to 50% agreement	30 to <40% agreement	< 30% agreement	< 10 Observations

For changes in ventilation (PIP or vent rate) each ABG/ventilator setting combination was categorized into the boxes on the above ventilation table. The direction of change to VR and PIP which clinicians chose was compared to the direction of change of the ventilator protocol's recommendation. (a) All observations ($N = 2{,}719$), while (b) includes observations from patients with bilateral pulmonary infiltrates (ALI cohort, $N = 1{,}415$). Colors represent percent agreement with ventilator protocol recommendations: >50% agreement (green), 40–50% (yellow), 30–40% (orange), <30% (red), excluded cells (<10 observations, gray). Note that changes to PIP and VR are similar between the ALI cohort and the entire cohort, particularly when pH is >7.30

than 7.45. This was also true for subgroups of patients with bilateral infiltrates, or without co-morbidities that may affect ventilator practice (i.e., increased airway resistance, pulmonary hypertension, and intracranial hypertension).

We used our pediatric mechanical ventilation protocol as a framework to examine variability in clinician decision making. We evaluated the potential acceptability of the protocol by comparing actual changes to changes the protocol would have recommended given the same patient state. Because of the variability in change size (e.g., one provider weans PIP by 2 cmH_2O, another provider by 4 cmH_2O), we evaluated the direction but not the size of change. If the protocol is actually representative of best available evidence (based on adult studies and expert review by pediatric intensivists), then times when clinician responses differed from protocol recommendations might represent missed opportunities to improve lung protective ventilation practices. We identified 38% of physician responses to ABGs as potential missed opportunities to reduce FiO_2 (Table 3), and 46% as potential missed opportunities to decrease PIP or ventilator rate (Table 5). This assumes that physicians would have followed 100% of the computer protocol recommendations—something we cannot know.

This pediatric mechanical ventilation computer protocol has not been formally validated against clinically important outcomes such as VFDs or mortality. Its actual benefits are unknown, and prospective validation studies are needed.

Table 5 Variability in ventilation decisions for similar patient states

Cell	pH	PIP	VR	Recommendation	N = 2,719	No Change N	No Change %	In Line N	In Line %	Opposite N	Opposite %	Combination N	Combination %
1	> 7.45	≤ 28	All	↓PIP 2; ↓VR by 20%	317	143	45.1	158	49.8	19	6	3	0.9
2	7.30 - 7.45	≤ 28	All	↓PIP 2	1021	651	63.8	223	21.8	155	15.2	8	0.8
3	7.15 – 7.29	≤ 28	< 25	↑PIP 2; ↑VR by 20%	126	57	45.2	61	48.4	13	10.3	5	4
4	7.15 – 7.29	≤ 28	≥ 25	↑PIP 4	62	23	37.1	30	48.4	13	21.0	4	6.5
5	< 7.15	≤ 28	< 25	↑PIP 4; ↑VR by 20%	13	3	23.1	10	76.9	1	7.7	1	7.7
6	< 7.15	≤ 28	≥ 25	↑PIP 4	5	3	60	2	40	0	0	0	0
7	> 7.45	29-35	All	↓PIP 2	201	101	50.2	85	42.3	18	9	3	1.5
8	7.30 - 7.45	29-35	All	↓PIP 2	473	288	60.9	127	26.9	67	14.2	9	1.9
9	7.15 – 7.29	29-35	< 25	No Δ PIP; ↑VR	84	38	45.2	35	41.7	15	17.9	4	4.3
10*	7.15 – 7.29	29-35	≥ 25	No Δ PIP	82	44*	53.7	27	32.9	14	17.1	3	3.7
11	< 7.15	29-35	< 25	↑PIP 2; ↑VR by 20%	9	2	22.2	6	66.7	1	11.1	0	0
12	< 7.15	29-35	≥ 25	↑PIP 2	13	5	38.5	5	38.4	4	30.8	1	7.7
13	> 7.45	> 35	All	↓PIP 4	47	17	36.2	28	59.6	2	4.3	0	0
14	7.30 - 7.45	> 35	All	↓PIP 2	146	78	53.4	55	37.7	15	10.3	2	1.4
15**	7.15 – 7.29	> 35	< 25	↓PIP 2; ↑VR by 20%	37	18	48.7	8	21.6	13	35.1	2**	5.4
16	7.15 – 7.29	> 35	≥ 25	↓PIP 2	56	25	44.6	22	39.3	15	26.7	6	10.7
17	< 7.15	> 35	< 25	↑VR by 20%	6	3	50	2	33.3	1	16.7	0	0
18*	< 7.15	> 35	≥ 25	No Δ PIP	21	10*	47.6	6	28.5	8	38.1	3	14.3

The left-hand side of the table summarizes the recommendations based on the blood gas, PIP, and VR from the pediatric mechanical ventilator protocol. The right-hand side describes the changes in PIP or VR made by clinicians in actual practice in response to a blood gas. The middle column (blue shaded cells) represents the number of observations per cell in the ventilation table. The columns to the right of that display the number and percentage of observations in each cell for which clinicians made no change to VR or PIP, changed VR or PIP in the same direction as the protocol recommendation, changed VR or PIP opposite to the protocol recommendation, or made a combination of increasing one parameter (VR or PIP) and decreasing the other (VR or PIP)

PIP peak inspiratory pressure (cmH_2O), *VR* ventilator rate (bpm)

* In these two cells the protocol would have recommended no change to PIP or VR; for these cells in line means VR or PIP was increased, opposite means PIP or VR was decreased

** In this cell the protocol recommended increasing the VR and decreasing the PIP; for this cell in line means VR or PIP was increased, opposite means PIP or VR was decreased

However, prior to prospective studies of the protocol, it must first be acceptable to clinicians. From our current analysis, the behavior of clinicians was directly contradictory to the computer protocol's recommendations on average 11% of the time (Table 5). We cannot be sure of the circumstances surrounding clinicians' decisions from this retrospective data. Clinicians could have been responding to changes in noninvasive measurements of oxygenation or ventilation, as we used pulse oximetry and capnography routinely in our PICU. This information would not have been captured if no ABG measurements had been obtained. This low (11%) rate of direct contradiction suggests that the computer protocol is, in general, consistent with current practice and is likely acceptable to pediatric clinicians.

We may also need to refine certain protocol recommendations such as the modified ventilator rate stratification of 25 bpm. In practice, clinicians escalated ventilator rate above 25 bpm in nearly a quarter of the cases (Table 2). Perhaps the original adult cutoff of

35 bpm is appropriate for pediatrics as well. This may also be the case for the proposed reduction of FiO_2 step changes to 0.05, as physicians appear to make almost as many 0.1 changes. We plan to refine the protocol by analyzing "controversial" cells through directed scenarios. This will involve multiple clinicians from multiple institutions with the intent of making the protocol generalizable to other PICUs. This may help achieve a balance between adherence to the protocol's recommendations and the degree of lung protection recommended by the protocol.

Our analysis has limitations. We could not elucidate the reasons for clinician decisions. It is possible that clinicians used other data (e.g., end tidal CO_2 or pulse oximetry) or factors surrounding the patient's care (e.g., hemodynamics or sedation) in their ventilator decisions. Moreover, decision making during the 7-year study period could have evolved. However, there did not appear to be a significant effect of time when we compared data from 2000 to 2003 with data from later years (2004–2007; analysis not shown). Nonetheless, the clear trends and consistent findings from a large number of observations from well over 40 critical care physicians give strength to our conclusions.

Conclusions

Although pediatric critical care practitioners have embraced lung protective ventilation, ventilator management is variable, with lost opportunities to minimize potentially injurious ventilator settings. A computer ventilator management protocol might prompt consistent ventilator changes to encourage lung protective decisions.

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