Impact of Height Estimation on Tidal Volume Calculation for Protective Ventilation—A Prospective Observational Study

André R. Alexandre, MD

Filipa R. Rocha, MD

Luís Landeiro, MD

Pedro Mota, MD

Joana Jones, MD

José A. Gomes, MD

OBJECTIVES: The current standard of care to deliver invasive mechanical ventilation support is the protective ventilation approach. One pillar of this approach is the limitation of tidal volume to less than 6 mL/Kg of predicted body weight. Predicted body weight is calculated from patient's height. Yet, little is known about the potential impact of errors arising from visual height estimation, a common practice, to calculate tidal volumes. The aim of this study was to evaluate that impact on tidal volume calculation to use during protective ventilation.

DESIGN: Prospective observational study.

SETTING: An eight-bed polyvalent ICU.

PATIENTS: Adult patients ($\geq$ 18 yr).

INTERVENTIONS: None.

MEASUREMENTS AND MAIN RESULTS: Tidal volumes were calculated from visual height estimates made by physicians, nurses, and patients themselves and compared with tidal volumes calculated from measured heights. Comparisons were made using the paired t test. Modified Bland-Altman plots were used to assess agreement between height estimates and measurements. One-hundred patients were recruited. Regardless of the height estimator, all the mean tidal volumes would be greater than 6 mL/Kg predicted body weight (all $p < 0.001$). Additionally, tidal volumes would be greater than or equal to 6.5 mL/Kg predicted body weight in 18% of patients' estimates, 25% of physicians' estimates, and 30% of nurses' estimates. Patients with lower stature (< 165 cm), older age, and surgical typology of admission were at increased risk of being ventilated with tidal volumes above protective threshold.

CONCLUSIONS: The clinical benefit of the protective ventilation strategy can be offset by using visual height estimates to calculate tidal volumes. Additionally, this approach can be harmful and potentially increase mortality by exposing patients to tidal volumes greater than or equal to 6.5 mL/Kg predicted body weight. In the interest of patient safety, every ICU patient should have his or her height accurately measured.

KEY WORDS: acute respiratory distress syndrome; body height; critical care; intensive care units; pulmonary ventilation; quality improvement

The current standard of care to deliver invasive mechanical ventilation support is the protective ventilation strategy (1). In particular, this strategy showed a beneficial impact on clinical outcomes, including a 22% relative reduction in mortality, during the treatment of patients with acute

respiratory distress syndrome (ARDS) (2). The protective ventilation approach includes the following settings: use of low tidal volume (< 6 mL/Kg of predicted body weight (PBW]), limitation of the plateau pressure to less than 30 cm H_2O, and use of positive end-expiratory pressure (PEEP) of greater than or equal to 5 cm H_2O (1).

To determine the adequate tidal volume (Vt) to deliver during protective ventilation, it is necessary to calculate the patient's PBW. This is accomplished by using the Devine's formulas (3) adjusted by gender:

- Male: PBW = 50 + 0.91 × (height in cm–152.4) Kg
- Female: PBW = 45.5 + 0.91 × (height in cm–152.4) Kg

As shown, these formulas depend on the patient's height. Unfortunately, both height and PBW are mostly estimated during the assessment of critically ill patients at bedside, and these estimations are thought to be biased and inaccurate (4–6). Previous studies (7–9) demonstrated that direct visual PBW estimation is common and often leads to the administration of Vt outside the protective ventilation range. Yet, little is known about the potential impact of errors arising from visual height estimation to calculate Vt to use during protective ventilation.

We hypothesize that visual height estimation may lead to errors in height assessment with multiple clinical repercussions. The delivery of unsafe Vt during invasive mechanical ventilation, with potentially deleterious effects on patient outcome, may be one of those consequences. To address this issue, we designed this study with the aim of evaluating the impact of visual height estimation on Vt calculation to use during protective ventilation.

MATERIALS AND METHODS

Study Design and Setting

We conducted a prospective observational study at the ICU of Hospital da Luz—Lisboa, an eight-bed polyvalent ICU integrated at a private hospital in Portugal. The enrollment period extended from July 2018 to May 2019. The study was approved by the Institutional Ethics Committee (CES/26/2018/ME), and all participants or their representatives signed informed consent before enrollment. All study procedures were conducted in accordance with the Declaration of Helsinki.

Study Population

We enrolled participants in this study by doing a convenience sampling of patients admitted to our ICU during the study period. To be eligible for enrolment, patients had to be 18 years old or older and willing to give informed consent for study participation. Informed consent could be given by a next of kin if the patient was unable to sign it. Patients admitted exclusively to perform invasive procedures (including elective sessions of renal replacement therapy), higher than 215 cm or with bilateral amputation of the feet, were excluded. Ongoing or planned invasive mechanical ventilatory support was not needed to enrollment. Only the patient's first ICU admission during the same hospital stay was considered eligible to study entry. Enrollment took place at the first day of ICU admission.

Data Collection

For every enrolled patient, we collected information on demographics (age, gender), typology of admission (medical vs surgical), worse registered value of two severity/prognostic scores during the first 24 hours of ICU admission (Acute Physiology and Chronic Health Evaluation [APACHE] II [10] and Simplified Acute Physiology Score II [SAPS II] [11]), and the patient's visual height estimation from the physician and the nurse who performed the admission. The physician was blinded to the nurse estimation and vice versa. The physicians who performed the estimations were four residents and eight senior intensivists. All nurses taking part in the study were experienced in intensive care.

We then collected the patient's own height estimation or, when impossible, the patient's visual height estimation from a next of kin. Finally, an exact crown-to-heel measurement of the patient's real height, in dorsal decubitus and with the bed at 0°, was performed with a measuring 215-cm calliper. Every height measurements and estimations were registered in cm.

Height estimations and measurements were used to calculate the PBW for every patient using the Devine's formulas (3). The resulting PBWs were used to calculate the Vt to use during protective ventilation by being multiplied by 6 mL/Kg. If the patients needed to be mechanically ventilated, only the real heights measured with the calliper were used to calculate the Vt to deliver.

Finally, we divided every Vt calculated from the visual height estimates by the real PBW derived from the measured height (formula below). This last step originated the equivalent Vt (exposed Vt) that the patient would be exposed to if the visual height estimation was followed to calculate the PBW and the Vt. Exposed Vt were analyzed in three categories as suggested by Needham et al (12): less than 6.5, 6.5–8.5, and greater than 8.5 mL/Kg PBW.

- Exposed Vt (mL/Kg PBW) = estimated Vt/PBW calculated from the measured height

Study Size

We hypothesized that a greater than or equal to 5–10 mL difference in Vt above the 6 mL/Kg of PBW threshold for protective ventilation calculated from the real height would be significant. We calculated that we would need a sample of 73 patients to demonstrate the presence of such a difference with an alpha level of 0.05 and a power of 80%. To be conservative, we extended the enrollment to 100 patients.

Statistical Analysis

We performed a descriptive statistical analysis of the patients' characteristics, presenting continuous variables as means ± SD, if normally distributed, or as medians and interquartile range, if not normally distributed. The presence of a normal distribution was assessed graphically. Categorical variables were presented as proportions or percentages.

We compared every Vt derived from the visual height estimations (physician, nurse, patient/family) with the Vt calculated from the real height measurement by using the paired t test. Additionally, to assess the agreement between visual height estimations and real height measurement, we constructed modified Bland-Altman plots. In these graphics, we plotted the
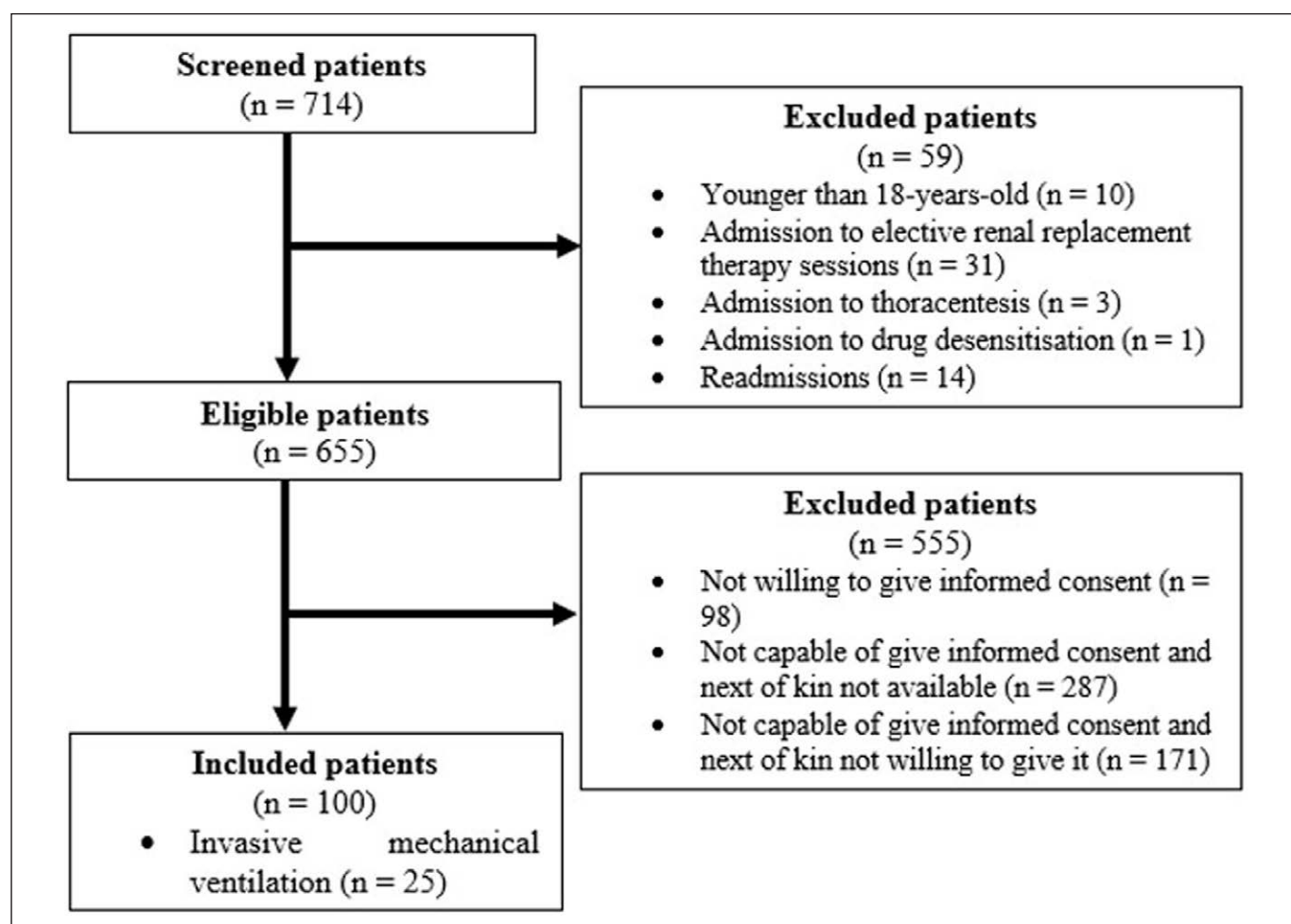
Figure 1. Flowchart of study participants.

real heights in *x*-axis against the difference between the visual estimate and real height measurement in the *y*-axis. We also performed a prespecified subgroup analyses by gender, age class (< 65 vs ≥ 65 yr old), stature category (< mean height vs ≥ mean height of our sample), and typology of admission for the three groups of height estimation. Data were analyzed by STATA 15 (StataCorp, College Station, TX). All tests were two sided, and a *p* value of less than 0.05 was considered statistically significant.

RESULTS

During the study period, 714 patients were admitted to the ICU. One-hundred patients were enrolled. The patient flowchart is presented in **Figure 1**. The patients' baseline characteristics are summarized in **Table 1**. There was a preponderance of male patients (67%) and of admissions for surgical reasons (79%). The mean measured height was 165 ± 9 cm overall, with females showing lower stature than males. The modified Bland-Altman plots (**Fig. 2**) show that there was a tendency to overestimate the patients' heights regardless of whom made the estimate, especially in patients with lower statures. Overestimation of height leads to the calculation of above real PBW and of Vt superior to the protective ventilation threshold. Independently of the estimator, all the mean exposed Vt would be greater than 6 mL/Kg PBW (**Table 2**). Additionally, exposed Vt would be greater than or equal to 6.5 mL/Kg PBW in 18% of patients' estimates, 25% of physicians' estimates, and 30% of nurses' estimates. Patients with lower stature (< 165 cm) would be treated more frequently with exposed Vt greater than or equal to 6.5 mL/Kg PBW than taller patients (≥ 165 cm): 43% versus 12% by physicians' estimates, 40% versus 22% by nurses' estimates, and 31% versus 9% by patients' estimates.

The physicians overestimated patients' height in 73% of occasions. The difference between Vt calculated from physicians' height estimation and real height ranged from –49 to +104 mL. The estimated Vt was significantly above the protective ventilation Vt threshold (paired *t* test mean difference: 14.97 mL [CI 95%, 9.08–20.86 mL]; *p* < 0.001).

Overestimation was found on 72% of nurses' height estimations. The difference between Vt calculated from nurses' height estimation and real height ranged from –49 to +82 mL. The estimated Vt calculated was also significantly above the protective ventilation Vt threshold (paired *t* test mean difference: 14.22 mL [CI 95%, 8.68–19.76 mL]; *p* < 0.001).

Even the patients overestimated their height in 76% of occasions. The difference between Vt calculated from patients' height estimation and real height ranged from –66 to +109 mL. Also, these estimated Vt

TABLE 1.
Demographic and Clinical Characteristics of the Study Population

Demographic and Clinical Characteristics	Total (*n* = 100)	Male (*n* = 67)	Female (*n* = 33)
Age (yr), median (interquartile range)	74.5 (62–80)	75.0 (64–81)	71.0 (58–78)
Surgical admissions, *n* (%)	79 (79)	55 (55)	24 (24)
Medical admissions, *n* (%)	21 (21)	12 (12)	9 (9)
Acute Physiology and Chronic Health Evaluation II, median (interquartile range)	13.5 (10; 19)	14 (10; 18)	12 (8; 19)
Simplified Acute Physiology Score II, median (interquartile range)	27 (21.5–38)	28 (23–38)	25 (18–33)
Measured height (cm), mean ± SD	165 ± 9	170 ± 7	156 ± 7
Predicted body weight calculated from measured height (Kg), mean ± SD	60 ± 10	66 ± 6	49 ± 6
Tidal volume derived from measured height (mL), mean ± SD	362 ± 61	396 ± 38	295 ± 36

Values are , or median (interquartile range)
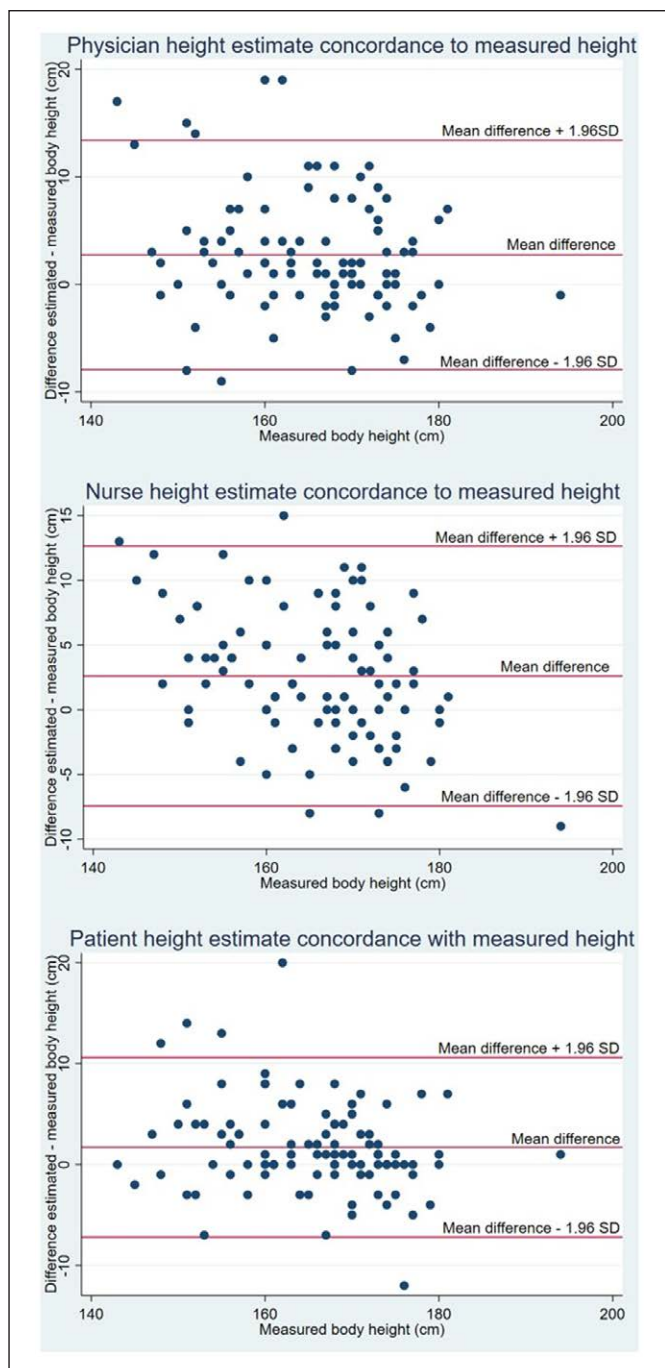
Figure 2. Bland-Altman plots comparing measured height with visual estimated height by estimator.

was significantly above the protective ventilation Vt threshold (paired *t* test mean difference: 9.39 mL [CI 95%, 4.45–14.33 mL]; *p* < 0.001).

In the subgroup analysis, at an alpha level of 0.05, only the Vt calculated from the physicians' and patients' visual height estimations of patients with a medical typology of admission and of patients with a stature greater than or equal to 165 cm did not

reach statistical significance for being above the protective ventilation Vt threshold. But after using the Bonferroni correction for the multiple comparisons done in the subgroup analysis (using an alpha level of 0.006), this lack of statistical significance was extended to all patients younger than 65 years old, with a medical typology of admission and with a stature greater than or equal to 165 cm, regardless of whom did the height estimation. Additionally, statistical significance was also not found for patients' height estimation in both gender subgroups. Subgroup analysis results are detailed in **Table 3**.

DISCUSSION

Our study shows that the use of visual height estimation to calculate Vt in the setting of protective ventilation delivery is inaccurate. In fact, errors arising from this common estimation practice tend to amplify through PBW calculation using Devine's formulas (3), followed by PBW multiplication to determine desired Vt. Albeit this inaccuracy might be potentially harmful, we cannot conclude it from our study design.

All three estimators we tested (physicians, nurses, and patients) would lead to the delivery of Vt above protective ventilation threshold in most cases. Physicians would deliver a mean exposed Vt of 6.3 ± 0.6 mL/Kg PBW, whereas nurses would deliver 6.3 ± 0.5 mL/Kg PBW and patients 6.2 ± 0.5 mL/Kg PBW (5%, 5% and 3.3% above the protective threshold, respectively).

Similarly to Sasko et al (13), we found that the real body height has an impact on the accuracy of the visual estimates. Height of patients with lower statures was frequently overestimated, whereas the height of taller patients was more underestimated. The agreement between estimated and real height was particularly poor at the extremes of height. This phenomenon is called "regression effect," a statistical bias of the estimates toward the mean value of the underlying distribution, as described by Petzschner et al (14).

The clinical significance of our findings is expressed by the expected increase in mortality at 2 years for patients with acute lung injury by being ventilated with a Vt greater than or equal to 6.5 mL/Kg PBW, as reported by Needham et al (12). In that study, it was reported an 18% increase in mortality for every 1 mL/Kg PBW increase in Vt, with an hazard ratio for mortality of 1.59 for mean Vt of 6.5–8.5 mL/Kg PBW

TABLE 2.
Visual Height Estimates and Derived Predicted Body Weight, Tidal Volumes, Exposed Tidal Volumes and Exposed Tidal Volume Class Percentages by Estimator

	Physician Estimation			Nurse Estimation			Patient Estimation		
Estimated height (cm), mean ± SD	168 ± 9			168 ± 9			167.2 ± 9.4		
PBW from estimated height (Kg), mean ± SD	63 ± 10			63 ± 10			62 ± 10		
Tidal volume from estimated height (mL), mean ± SD	377 ± 57			377 ± 57			372 ± 61		
Exposed tidal volume (mL/Kg PBW), mean ± SD	6.3 ± 0.6			6.3 ± 0.5			6.2 ± 0.5		
Exposed tidal volume class (mL/Kg PBW), %	< 6.5	6.5–8.5	> 8.5	< 6.5	6.5–8.5	> 8.5	< 6.5	6.5–8.5	> 8.5
	75	24	1	70	30	0	82	18	0

PBW = predicted body weight.

and of 1.97 for greater than 8.5 mL/Kg PBW. In our sample, this increased risk of mortality would affect 25% of patients if physicians' height estimates would be used to Vt calculation and 30% if nurses' estimates were used instead. Even if only patients' estimates were used, 18% of patients would be exposed to this potentially increased risk of mortality. The percentage of patients that would be exposed to increased mortality risk is even more striking in lower statute group (< 165 cm), reaching 43% by utilization of physicians' estimates, 40% by nurses' estimates, and 31% by patients' estimates.

From the referred findings, it becomes obvious that lower stature was a risk factor to receive ventilation with Vt above 6 mL/Kg PBW. That risk has been previously reported (13, 15) and was confirmed by our subgroup analysis that showed Vt significantly above the protective threshold for lower stature patients (< 165 cm) regardless of the estimator, but not to taller ones (≥ 165 cm). Other risk groups for receiving Vt above the protective threshold resulting from the performed subgroup analysis were older patients (≥ 65 yr old) and patients with a surgical typology of ICU admission. For older patients, we can hypothesize that the tendency to the overestimation of height results from stature reduction with ageing (16) that might be difficult to perceive in the supine position. The height overestimation in surgical patients might be related to their lower mean APACHE II a SAPS II scores when compared with medical patients in our sample. These three risk groups are consistent with the risk factors

to not being ventilated with protective parameters reported by Walkey et al (15).

From our findings, we can conclude that visual height estimation reduces the probability of delivering protective ventilation to patients. In daily practice, visual height estimation seems to be commonly done with only one third of Vt calculated as recommended by guidelines (8). The real impact of this estimation practices has been analyzed only once (13) but never in the context of mandatory accurate Vt as in ARDS patients. If basic principles of protective ventilation are undermined by practices like visual height estimation, discussion of complex ventilatory strategies is pointless. Measuring the height of all ventilated patients with a calliper is a simple and cheap solution that could increase patient safety.

Particularly in ARDS patients, a different approach to Vt adjustment has been suggested by Amato et al (17). The authors tested the hypothesis that driving pressure (the ratio of Vt to respiratory system compliance) considers the decrease in functional lung capacity during ARDS. Since driving pressure can be calculated at the bedside as the difference between plateau pressure and PEEP, in patients with no ventilatory effort, and compliance is given by the ventilator, it could be a better way to adjust the Vt during protective ventilation. This is particularly attractive by allowing a dynamic adjustment of Vt to functional lung size without accounting to height and PBW which are static and frequently estimated. Additionally, the authors found that driving pressure was the ventilator variable with the strongest

TABLE 3.
Paired *t* Test Subgroup Comparison of Mean Tidal Volume Difference by Author of Height Visual Estimation

		Physician Estimation		Nurse Estimation		Patient Estimation	
		Mean Vt Difference (CI 95%) mL	*p*	Mean Vt Difference (CI 95%) mL	*p*	Mean Vt Difference (CI 95%) mL	*p*
Gender	Male (*n* = 67)	14.31 (6.97–21.66)	< 0.001	12.03 (4.93–19.13)	0.001	8.36 (2.23–14.48)	0.008
	Female (*n* = 33)	16.30 (5.92–26.69)	0.003	18.67 (9.74–27.60)	< 0.001	11.48 (2.74–20.23)	0.011
Age class, yr	< 65 (*n* = 30)	8.8 (0.68–16.92)	0.035	12.73 (2.31–23.15)	0.018	8.23 (1.03–15.43)	0.027
	≥ 65 (*n* = 70)	17.61 (9.91–25.32)	< 0.001	14.86 (8.15–21.56)	< 0.001	9.89 (3.44–16.33)	0.003
Typology of admission	Surgical (*n* = 79)	16.31 (9.62–22.99)	< 0.001	13.92 (7.71–20.14)	< 0.001	8.42 (3.22–13.61)	0.002
	Medical (*n* = 21)	9.95 (−3.40 to 23.30)	0.135	15.33 (2.01–28.66)	0.026	13.05 (−0.98 to 27.07)	0.067
Stature, cm	< 165 (*n* = 42)	26.48 (16.72–36.23)	< 0.001	22.67 (14.62–30.71)	< 0.001	17.24 (8.16–26.32)	< 0.001
	≥ 165 (*n* = 58)	6.64 (−0.12 to 13.40)	0.054	8.10 (0.74–15.47)	0.032	3.71 (−1.46 to 8.87)	0.156

Vt = tidal volume.

association with survival in ARDS. Survival improved with ventilator adjustments that lead to decreases in driving pressure (ideally below 13–15 cm H_2O) (18) limiting lung overstress and overstrain. Although this approach has been previously discussed by different authors (19–21), until today, no prospective studies addressing the effect of driving pressure as a primary goal during ventilation of ARDS patients have been published (22). Accounting for that lack of evidence, effective height measurement to PBW and Vt calculation continues to be the recommended approach.

This study had multiple limitations. First, because of its observational design, only with simulation of ventilation settings derived from height estimation, it is impossible to draw conclusion on the actual impact of that estimation on clinical outcomes. We tried to address that limitation by using the categories of Vt suggested by Needham et al (12) to predict mortality extrapolated to our study. Second, since the ventilator settings derived from height estimation would be only simulated, we included patients independently of their need for invasive ventilation to maximize recruitment. Nevertheless, that decision might have been a source of bias to the results. Third, the protective ventilation strategy includes other ventilator settings beyond low Vt that were not addressed in our study. Last, this was a single-center study at a Portuguese private hospital. Since the enrolled study sample was predominantly composed of Caucasian males, mainly admitted for surgical reasons with low severity scores, the generalizability of the findings is limited and needs confirmation in different contexts.

CONCLUSIONS

In conclusion, the clinical benefit of the protective ventilation strategy can be offset by using visual height estimates. Those estimates are mainly inaccurate,

promote error accumulation, and can lead to administration of Vt above protective ventilation threshold in most situations. This approach may increase mortality by exposing patients to Vt greater than or equal to 6.5 mL/Kg PBW. Patients with lower statute, older age, and admitted for surgical reasons are at increased risk of being exposed to nonprotective ventilation. In the interest of patient safety, every ICU admitted patient should have his or her height accurately measured with a calliper irrespective of any time or budget constraints.

ACKNOWLEDGMENTS

All authors: Department of Intensive Care, Hospital da Luz – Lisboa, Lisboa, Portugal.

For information regarding this article, E-mail: andrerosaalexandre@gmail.com

REFERENCES

1. Papazian L, Aubron C, Brochard L, et al: Formal guidelines: Management of acute respiratory distress syndrome. *Ann Intensive Care* 2019; 9:69

2. Brower RG, Matthay MA, Morris A, et al; Acute Respiratory Distress Syndrome Network: Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. *N Engl J Med* 2000; 342:1301–1308

3. Devine B: Gentamicin therapy. *Drug Intell Clin Pharm* 1974; 8:650–655

4. Bloomfield R, Steel E, MacLennan G, et al: Accuracy of weight and height estimation in an intensive care unit: Implications for clinical practice and research. *Crit Care Med* 2006; 34:2153–2157

5. Leary TS, Milner QJ, Niblett DJ: The accuracy of the estimation of body weight and height in the intensive care unit. *Eur J Anaesthesiol* 2000; 17:698–703

6. Young M: Estimated versus measured height and weight in the intensive care unit: How do ICU clinicians measure up? *Crit Care Med* 2006; 34:2251–2252

7. Diacon AH, Koegelenberg CF, Klüsmann KJ, et al: Challenges in the estimation of tidal volume settings in critical care units. *Intensive Care Med* 2006; 32:1670–1671

8. Tallach R, Jefferson P, Ball DR: Mechanical ventilation for patients with ARDS: A UK survey on calculation of tidal volume. *Intensive Care Med* 2006; 32:176

9. Kam EP, Eslick GD, James A, et al: Acute respiratory distress syndrome (ARDS) and low tidal volume ventilation: The debate about weight. *Intensive Care Med* 2004; 30:1502

10. Knaus WA, Draper EA, Wagner DP, et al: APACHE II: A severity of disease classification system. *Crit Care Med* 1985; 13:818–829

11. Le Gall JR, Lemeshow S, Saulnier F: A new simplified acute physiology score (SAPS II) based on a European/North American multicenter study. *JAMA* 1993; 270:2957–2963

12. Needham DM, Colantuoni E, Mendez-Tellez PA, et al: Lung protective mechanical ventilation and two year survival in patients with acute lung injury: Prospective cohort study. *BMJ* 2012; 344:e2124

13. Sasko B, Thiem U, Christ M, et al.: Size matters: An observational study investigating estimated height as a reference size for calculating tidal volumes if low tidal volume ventilation is required. *PLoS One* 2018; 13:1–14

14. Petzschner FH, Glasauer S, Stephan KE: A Bayesian perspective on magnitude estimation. *Trends Cogn Sci* 2015; 19:285–293

15. Walkey AJ, Wiener RS: Risk factors for underuse of lung-protective ventilation in acute lung injury. *J Crit Care* 2012; 27:323.e1–323.e9

16. Fernihough A, McGovern ME: Physical stature decline and the health status of the elderly population in England. *Econ Hum Biol* 2015; 16:30–44

17. Amato MB, Meade MO, Slutsky AS, et al: Driving pressure and survival in the acute respiratory distress syndrome. *N Engl J Med* 2015; 372:747–755

18. Aoyama H, Pettenuzzo T, Aoyama K, et al: Association of driving pressure with mortality among ventilated patients with acute respiratory distress syndrome: A systematic review and meta-analysis. *Crit Care Med* 2018; 46:300–306

19. Fuller BM, Page D, Stephens RJ, et al: Pulmonary mechanics and mortality in mechanically ventilated patients without acute respiratory distress syndrome: A Cohort Study. *Shock* 2018; 49:311–316

20. Schmidt MFS, Amaral ACKB, Fan E, et al: Driving pressure and hospital mortality in patients without ARDS: A Cohort Study. *Chest* 2018; 153:46–54

21. Bellani G, Laffey JG, Pham T, et al; LUNG SAFE Investigators; ESICM Trials Group: Epidemiology, patterns of care, and mortality for patients with acute respiratory distress syndrome in intensive care units in 50 Countries. *JAMA* 2016; 315:788–800

22. Aoyama H, Yamada Y, Fan E: The future of driving pressure: A primary goal for mechanical ventilation? *J Intensive Care* 2018; 6:64