Comparison of Usual and Alternative Methods to Measure Height in Mechanically Ventilated Patients: Potential Impact on Protective Ventilation

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BACKGROUND: Protective ventilation implementation requires the calculation of predicted body weight (PBW), determined by a formula based on gender and height. Consequently, height inaccuracy may be a limiting factor to correctly set tidal volumes. The objective of this study was to evaluate the accuracy of different methods in measuring heights in mechanically ventilated patients. METHODS: Before cardiac surgery, actual height was measured with a height gauge while subjects were standing upright (reference method); the height was also estimated by alternative methods based on lower leg and forearm measurements. After cardiac surgery, upon ICU admission, a subject's height was visually estimated by a clinician and then measured with a tape measure while the subject was supine and undergoing mechanical ventilation. RESULTS: One hundred subjects (75 men, 25 women) were prospectively included. Mean PBW was 61.0 ± 9.7 kg, and mean actual weight was 30.3% higher. In comparison with the reference method, estimating the height visually and using the tape measure were less accurate than both lower leg and forearm measurements. Errors above 10% in calculating the PBW were present in 25 and 40 subjects when the tape measure or visual estimation of height was used in the formula, respectively. With lower leg and forearm measurements, 15 subjects had errors above 10% ($P < .001$). CONCLUSIONS: Our results demonstrate that significant variability exists between the different methods used to measure height in bedridden patients on mechanical ventilation. Alternative methods based on lower leg and forearm measurements are potentially interesting solutions to facilitate the accurate application of protective ventilation. *Key words: protective mechanical ventilation; tidal volume; predicted body weight; height; ventilator-induced lung injury; acute lung injury; measure.* [Respir Care 2014;59(7):1025–1033. © 2014 Daedalus Enterprises]

Introduction

In patients with ARDS, ventilation with high tidal volumes (V_T) increases mortality, and protective ventilation with lower V_T is now widely recommended.[1-4] Several studies suggest that prophylactic protective ventilation should be

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used in most mechanically ventilated critically ill patients to avoid acquired ARDS[5-7] and to improve outcome.[6,8]

It is well established that a patient's lung volume is well correlated to height,[9] and this important physiologic value cannot be overlooked in mechanically ventilated patients. Indeed, protective ventilation implementation requires the calculation of predicted body weight (PBW) based on gender and height.[1] Consequently, height inaccuracy may be a limiting factor to adequately reduce the V_T. In this regard, it should be emphasized that PBW rather than actual body weight must be used to calculate the prescribed V_T.[8,10] The use of actual body weight can lead to large errors in V_T settings,[11] especially in women and obese patients.[8,12] Visual estimation of the patient's height is frequently used in mechanically ventilated patients.[13,14] However, visual estimation of height and, even more so, of PBW can be inaccurate.[15-18] In addition, despite strong evidence and recommendations, protective mechanical ventilation is not optimally implemented[19-23]; unavailability of the height may be an additional barrier.[11]

Considering the central role of the physiologic value of the patient's height and its impact on mechanical ventilation settings, we conducted this study to evaluate the accuracy of usual measurements of height in mechanically ventilated patients and to assess alternative measurements.

Methods

From July 2010 to December 2011, we conducted a prospective study to evaluate height measurement accuracy in patients requiring cardiac surgery at the Institut Universitaire de Cardiologie et de Pneumologie de Québec. Study approval was obtained from the local ethics committee, and informed consent was obtained from all subjects before surgery.

Subjects

The research coordinator screened patients before the surgery. The exclusion criteria were the inability of the patient to stand up for initial measurement, including emergent surgeries, and patients already on mechanical ventilation before surgery.

Study Measurements

Preoperatively. The reference method used for comparisons was the subject's actual height, measured with a height gauge while the subject was standing up. We also measured the lower leg length to calculate the height using the Chumlea method.[24-26] We measured the lower leg length with a special caliper while the subject was sitting with knees bent at a 90° angle. The length from the top of the knee (patella) to the bottom of the heel was measured. The subject's height was calculated using previously described equations.[26] In addition, we measured the subject's fore-

QUICK LOOK

Current knowledge

Implementation of a lung-protective ventilation strategy requires the calculation of predicted body weight, determined from a formula based on gender and height. Any error in the measurement of height can lead to inappropriately set tidal volumes and failure to provide lung protection.

What this paper contributes to our knowledge

A significant variability exists between the different methods of measuring height in bedridden mechanically ventilated patients. Alternative methods of determining height based on lower leg and forearm measurements are potential solutions to facilitate the accurate application of protective ventilation.

arm with a tape measure between the olecranon process of the elbow and the midpoint of the prominent styloid process of the radius. We then calculated the height based on a previously described chart.[27] Each measurement was performed only once for each subject, and two different investigators were involved in these measurements (Fig. 1).

Postoperatively. Within the first minutes after arriving at the ICU, other data were recorded while subjects were on mechanical ventilation. First, each subject's height was visually estimated by a nurse or a respiratory therapist and then subsequently measured by a nurse with a tape measure while the subject was supine in bed. Nurses and respiratory therapists were not aware of the subject's preoperative height (see Fig. 1). The PBW was calculated using the previously validated equations.[1]

Statistical Analysis

Data are presented as means ± SD. Categorical variables are presented as counts. Agreement between results was expressed by the Bland-Altman method,[28] and all data are presented using Bland-Altman plots. Estimated bias (average of the differences between the reference height [gauge] and the different measuring methods) and 95% CI (bias ± 1.96 × SD) were calculated. For errors of measurement, we calculated the mean of absolute difference between the reference and the different measuring methods. A generalized linear mixed model was performed using the normality or the binary model according to the data distribution. A compound symmetric structure was used to consider the dependence among measurements. Posteriori comparisons were performed using the Tukey technique.
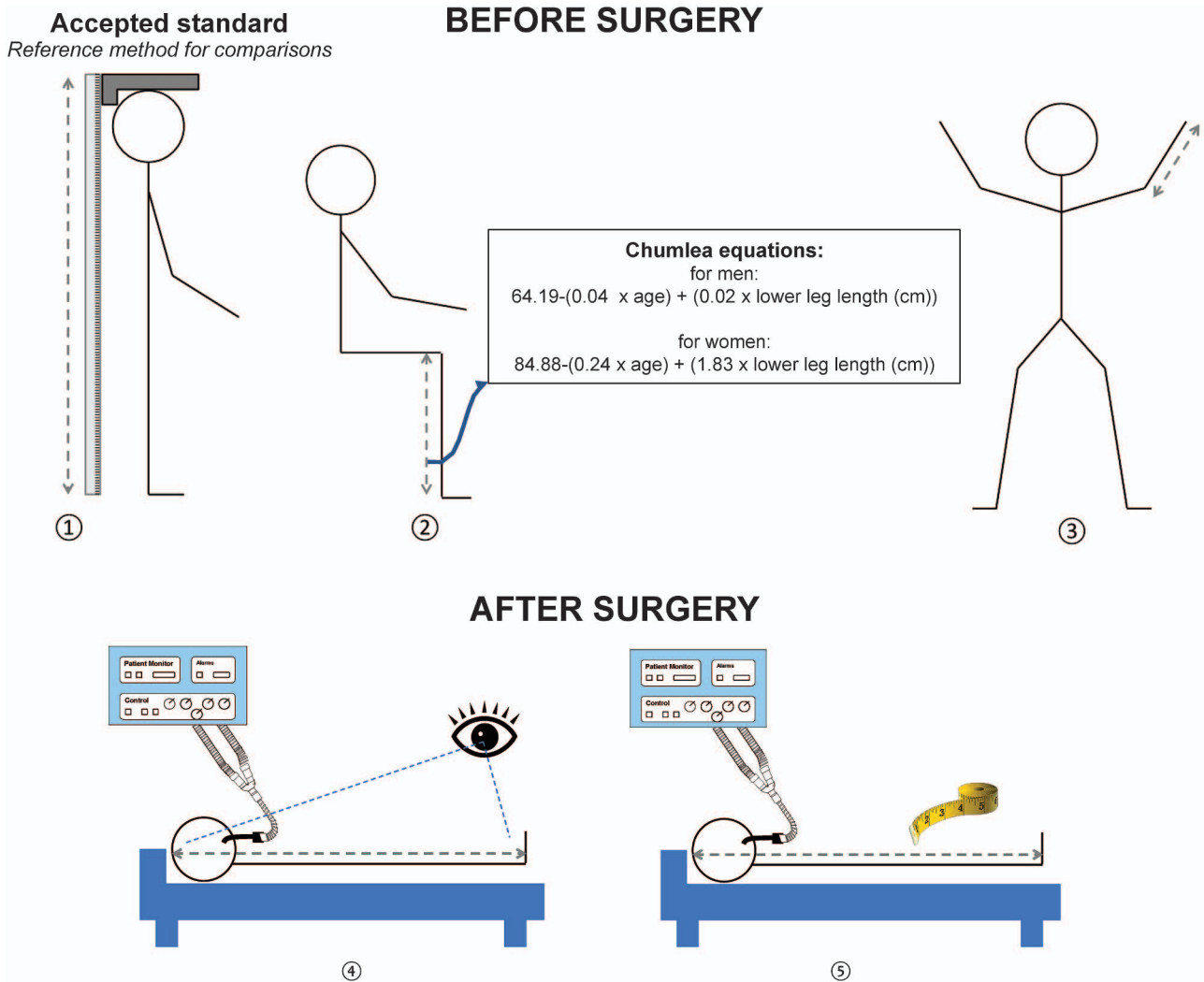
Fig. 1. Different methods to measure height. Five methods to obtain patient heights were compared. Preoperatively, subjects were measured with a height gauge while standing upright (1); this measure was used as the reference method. Lower legs (2) and forearms (3) were also measured, and subject height was derived from previously validated formulas.[26,27] Formulas to predict height based on lower leg measurement are provided, based on Reference 26. Postoperatively, heights were visually estimated (4) by one clinician, and (5) subjects (bedridden in a supine position) were subsequently measured with a tape measure.

Relationships between the reference and the other methods of measurement were analyzed using Pearson correlation coefficients. All reported P values were declared significant at .05. Data were analyzed using a statistical package (SAS 9.3, SAS Institute, Cary, North Carolina).

Results

Subjects

One hundred subjects (75 men, 25 women) with a mean age of 66.0 ± 9.3 y were studied. A total of 500 measurements of subjects' heights were obtained (5 measurements per subject). The mean actual weight was 79.5 ± 17.6 kg; the

mean PBW was 61.0 ± 9.7 kg. The median (interquartile) height measured by height gauge before surgery was 167 cm (159–174 cm). Data on height obtained with the different measuring methods and errors in comparison with the reference measure are shown in Table 1.

Differences Between Actual Height, Tape Measure Method, and Visual Estimation

The results obtained using a tape measure and visual estimation were well correlated with the reference (height gauge) (Fig. 2). Compared with the reference, bias with the tape measure was -3.7 ± 5.0 cm (95% CI -13.5 to 6.2), and bias with visual estimation was -4.0 ± 7.0 cm (95% CI -17.7

Table 1.   Difference Between Reference Values and Other Methods for Height Measurement

	Height Gauge (Reference)	Visual Estimation	Tape Measure	Lower Leg Measurement (Chumlea)	Forearm Measurement	P*
Height, mean ± SD, cm	165.8 ± 9.1	169.6 ± 8.3	169.4 ± 9.7	168.2 ± 9.0	167.2 ± 7.4	< .001
Bias, cm (95% CI)		−4.0 (−17.7 to 9.7)	−3.7 (−13.5 to 6.2)	−2.4 (−10.0 to 5.2)	−1.3 (−10.8 to 8.6)	
Error, mean ± SD, cm†		6.4 ± 4.8	4.7 ± 4.0	3.7 ± 2.6	3.7 ± 3.4	< .001
Maximum error, cm†		20.5	19.0	11.9	20	
Error, mean ± SD, %†		3.9 ± 3.1	2.9 ± 2.5	2.3 ± 1.6	2.3 ± 2.0	< .001
Subjects with error > 5%, n†		31	16	7	12	.002
Subjects with error > 10%, n†		5	2	0	1	.074
Subjects with error > 20%, n†		0	0	0	0	> .99

* The statistical method is the generalized linear model with repetitive measurements.
† Errors of measurement are comparisons with the reference value of height (measurement with height gauge before surgery while the subject was standing upright).
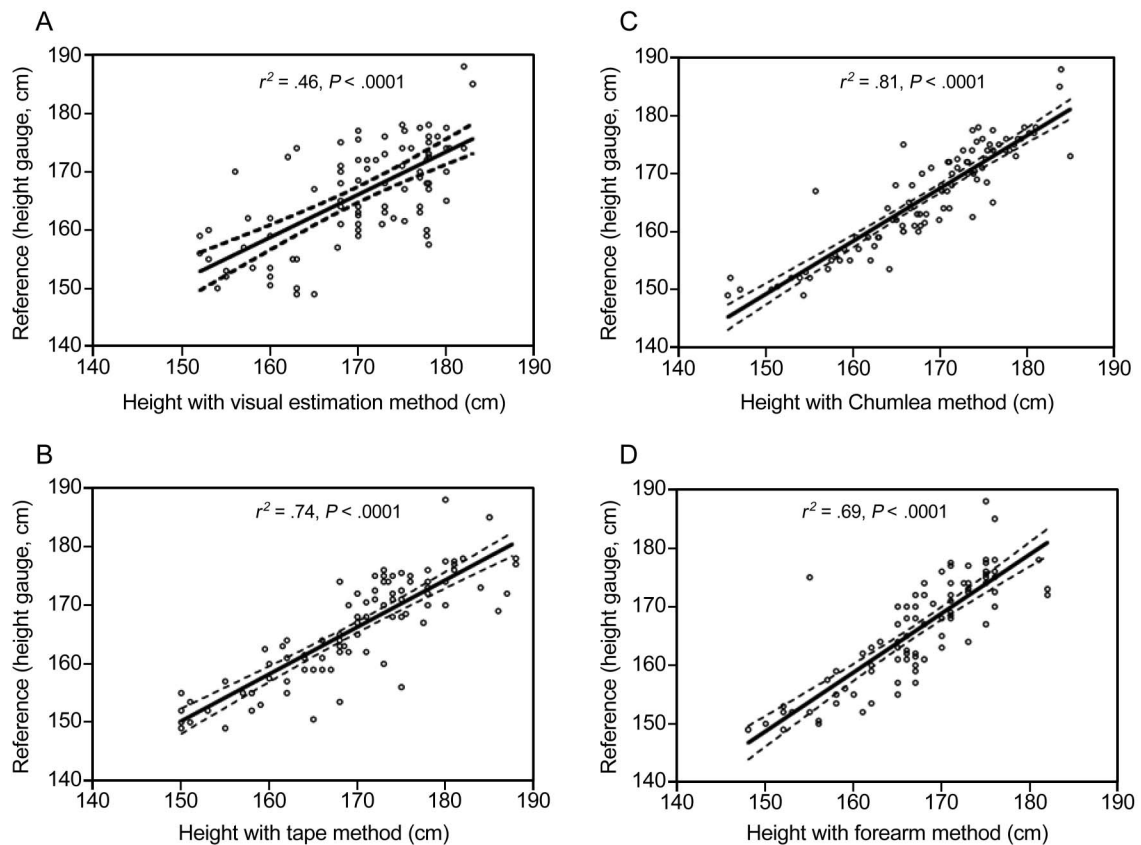

Fig. 2. Scatter plots with Pearson correlations between the reference values for height measurement and visual estimation (A), tape measure method (B), lower leg measurement (C), and forearm measurement (D). Solid lines represents the regression line, and dashed lines represent 95% CI.

to 9.7) (Fig. 3). Maximum errors with tape measure and visual estimation were 19.0 and 20.5 cm, respectively.

Error of visual estimation was inversely correlated to the subject's height (r = 0.52, P < .001). (See the sup-plementary materials at http://www.rcjournal.com.) Mean error of visual estimation was significantly greater with shorter subjects (those with a median height of ≤ 167 cm: 7.3 ± 6.7 vs 0.4 ± 5.5 cm, P < .001).
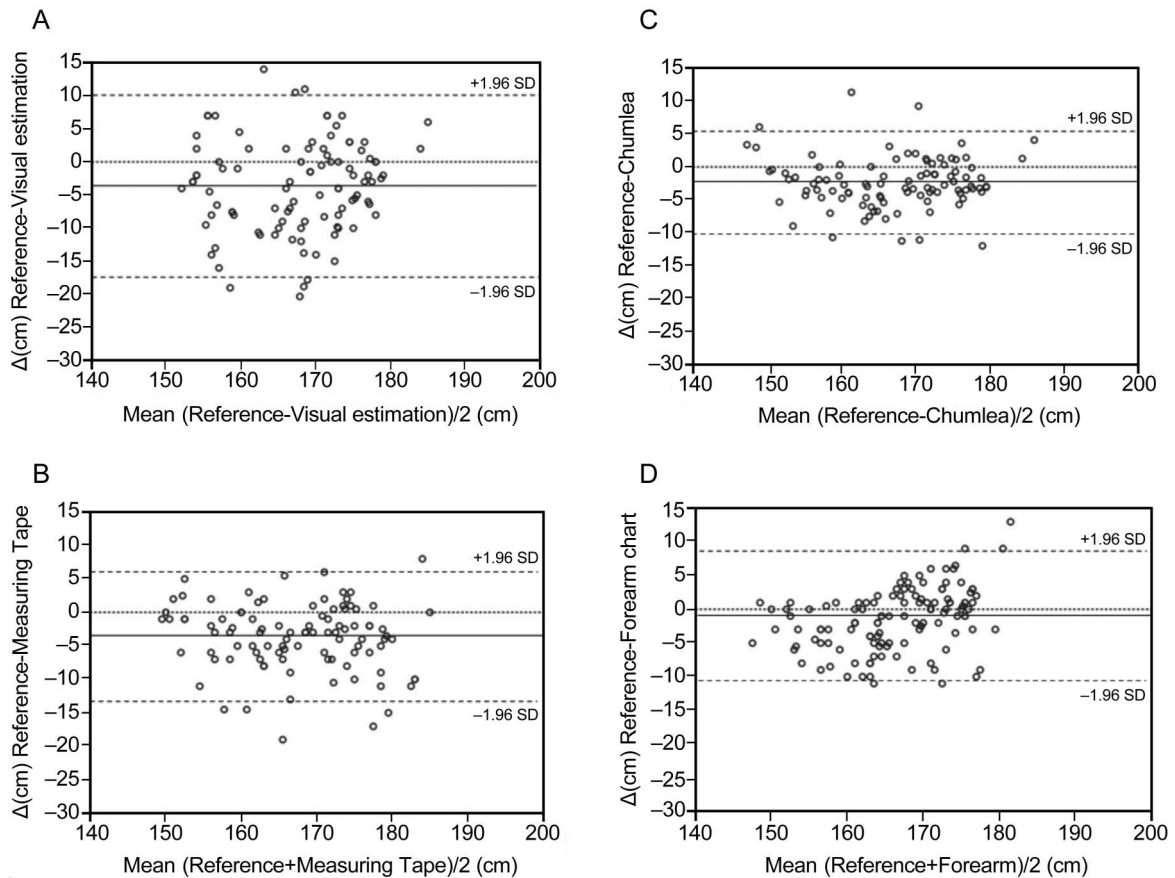
Fig. 3. Bland-Altman graph comparison of the reference value for height measurement and visual estimation (A), tape measurement (B), lower leg measurement (C), and forearm measurement (D). The solid lines represent the bias, and the dashed lines represent 95% CI.

Alternative Methods: Height Derived From Lower Leg (Chumlea Method) and Forearm Length

Height derived from the lower leg and forearm correlated well with height gauge (Fig. 2). Compared with the reference, bias with the lower leg was -2.4 ± 3.9 cm (95% CI -10.0 to 5.2), and bias with the forearm was -1.3 ± 5.0 cm (95% CI -10.8 to 8.6) (Fig. 3). Maximum errors with the lower leg and forearm methods were 11.9 and 20.0 cm, respectively.

Potential Impact on Protective Mechanical Ventilation

The mean actual body weight was 30.3% higher than the PBW, and differences in the calculation of V_T with actual body weight versus PBW were of similar amplitude. The errors for PBW were higher when the calculation of PBW was based on visually estimated heights and lower when the Chumlea method was used (Table 2). PBW errors of $> 10\%$ were present for 15% of the subjects when using the lower leg or forearm method, 25% when using a tape measure, and

40% when relying on visual estimation (Table 2). As expected, the error in V_T settings was marked when actual weight, rather than PBW, was used (Table 3). We compared the impact of the errors for shorter and taller subjects based on the median height of the subjects (ie, 167 cm). The actual weight was higher than the PBW, from $+21\%$ (in subjects > 167 cm) to $+35\%$ (in subjects ≤ 167 cm) (Table 3). In comparison with the V_T set with PBW, based on the reference height, maximal overestimation of V_T settings in short subjects changed from 396 mL with an actual weight to 82 and 73 mL with the lower leg and forearm methods, respectively (See the supplementary materials at http://www.rcjournal.com.). Among shorter subjects (≤ 167 cm), the proportion of women was 45.1% (23/51), whereas among taller subjects (> 167 cm), the proportion of women was only 4.1% (2/49, $P < .001$) (Table 3). Of those measuring less than the median height, 92% were women.

Discussion

Predicted rather than actual body weight should be used to determine the V_T required for mechanically ventilated pa-

Table 2. Differences in PBW Based on Reference Height and Other Measurement Methods

	Height Gauge (Reference)	Visual Estimation	Tape Measure	Lower Leg Measurement (Chumlea)	Forearm Measurement	P*
			PBW Based on			
PBW, mean ± SD, kg	61.0 ± 9.7	64.6 ± 8.8	64.4 ± 10.0	63.2 ± 9.7	62.7 ± 8.0	< .001
Bias, kg (95% CI)		−3.5 (−15.8 to 8.8)	−3.2 (−12.2 to 5.7)	−2.1 (−9.1 to 4.8)	−1.2 (−10.1 to 7.8)	
Error, mean ± SD, kg,†		5.7 ± 4.3	4.2 ± 3.6	3.4 ± 2.4	3.5 ± 3.1	< .001
Maximum error, kg†		18.7	17.3	10.9	18.2	
Error, mean ± SD, %†		10.0 ± 8.5	7.2 ± 6.8	5.8 ± 4.3	6.0 ± 5.4	< .001
Subjects with error > 5%, n†		63	48	41	45	.005
Subjects with error > 10%, n†		40	25	15	15	< .001
Subjects with error > 20%, n†		9	7	0	1	.03

The number of subjects with errors above 5, 10, and 20% with actual body weight compared with predicted body weight (PBW) was 88, 78, and 63, respectively.
* The statistical method is the generalized linear model with repetitive measurements.
† Errors are comparisons with the PBW calculated with the reference value of height (measurement with height gauge before surgery while the subject was standing upright).

Table 3. Impact of Height Measurement Method on V_T Setting

	Subjects With Height > 167 cm (n = 49)*	Subjects With Height < 167 cm (n = 51)*
Female, n (%)	2 (4.1)	23 (45.0)
Age, y	63 (57–68)	71 (63–75)
BMI, kg/m²	26.5 (22.7–31.0)	28.4 (26.7–30.5)
Height		
Based on height gauge (reference)	174 (171–176)	159 (153–162)
Based on lower leg	175 (172–178)	163 (157–167)
Based on forearm	173 (170–175)	163 (158–166)
Based on visual estimation	175 (170–178)	165 (159–171)
Based on Tape measure	176 (173–180)	162 (158–168)
Weight, kg		
Actual weight	83.8 (73.8–94.1)	73.2 (61.3–81.3)
PBW based on height gauge (reference)	69.2 (66.4–71.5)	54.2 (47.2–58.7)
PBW based on lower leg	70.2 (68.2–73.4)	57.4 (49.9–63.2)
PBW based on forearm	68.7 (66.5–70.6)	58.7 (50.6–62.8)
PBW based on visual estimation	70.6 (66.0–73.3)	59.7 (52.4–66.0)
PBW based on tape measure	71.5 (68.7–75.1)	57.0 (52.4–62.4)
V_T (8 mL/kg), mL		
Based on actual weight	670 (591–753)	585 (490–650)
Based on height gauge (reference)	554 (531–572)	434 (377–470)
Based on lower leg	562 (546–587)	459 (399–506)
Based on forearm	550 (532–565)	470 (405–503)
Based on visual estimation	565 (528–586)	478 (419–528)
Based on tape measure	572 (550–601)	456 (419–499)
Error in V_T compared with reference, mL†		
Based on actual weight	−118 (−192 to −41)	−130 (−202 to −94)
Based on lower leg	−12 (−24 to −9)	−27 (−42 to −12)
Based on forearm	7 (−5 to 22)	−29 (−51 to −7)
Based on visual estimation	−4 (−33 to 18)	−55 (−80 to −18)
Based on tape measure	−18 (−44 to 4)	−22 (−44 to −7)

Median (interquartile) values are reported. Minimum and maximum differences are provided. (See the supplementary materials at http://www.rcjournal.com.)
* 167 cm represents the median value for subjects' heights in this cohort.
† The error was calculated for a target of 8 mL/kg with the following formula: tidal volume (V_T) with height reference − V_T with other methods. Negative values correspond to overestimation of V_T.
BMI = body mass index
PBW = predicted body weight

tients.[1,8,10] However, the patient's height is required to calculate PBW.[1] We compared different direct and alternative methods to measure height in 100 bedridden mechanically ventilated subjects. We showed that significant differences exist between these methods (tape measure, visual estimation, and lower leg and forearm length) and the reference standard (gauge measurement). We found that visual estimation of height was an inaccurate method with large potential errors. The alternative methods, which were based on lower leg and forearm length, were close to the reference method and were at least as efficient as the tape measure method. This study represents the largest evaluation of different methods to assess height in bedridden subjects and demonstrates the potential impact on protective ventilation implementation.

Despite the paucity of data, several studies suggest that height is not being used to set the V_T[11,14] or that height is unknown because as many as 40% of ARDS patients had no height listed in their medical records,[29] and consequently, visual estimation of height or weight is frequently being used.[13,14,30] In surgical units, patients are frequently measured preoperatively. In a recent study, heights measured before surgery were available for 3,763 patients and were missing for only 6 patients (0.16%).[8] Although little data are available, it is likely that the tape measure method is also frequently used for medical bedridden patients when height is not known. In a survey of 20 ICUs in the United Kingdom, 15 measured patients with tape, and 5 estimated heights.[13] Our results show that visual estimation and the tape measure method while subjects are supine are not accurate, with maximum errors being ~20 cm. These errors were associated with large errors in V_T settings. Our results are in agreement with previous data that showed inaccuracy of visual estimations in different populations.[15-18,31,32] To our knowledge, there is no study evaluating accuracy of the tape measure method in bedridden patients in comparison with the reference method with a height gauge when patients are standing upright.

Several methods have been described to obtain a patient's height indirectly, among which lower leg measurement (knee-heel length, Chumlea method),[24-26] forearm measurement (from elbow to wrist), and demispan (distance from the middle of the sternal notch to the tip of the middle finger in the coronal plane) are the most frequently evaluated.[27,33] These alternative methods are potentially useful for bedridden patients or mobility-impaired patients.[24] For these patients, the tape measure method may be difficult to use (the subject's position in bed or the use of a short tape measure is a potential source of error) and may not be accurate, as we describe in this study. The use of a flexible tape measure to measure the lower leg is a potentially interesting solution.[34]

The Chumlea method, which allows height estimation based on knee-heel length, has been validated in large cohorts.[24-26,35] In elderly patients, who represent the majority of mechani-

cally ventilated subjects, this method was accurate in determining height.[25,26] Our study evaluated 2 indirect methods (based on lower leg and forearm measurements), and we showed that these methods were well correlated with the reference method and were at least as accurate in bedridden subjects as using tape measure. Maximum errors were equivalent (with forearm measurement) or lower (with lower leg measurement) in comparison with a tape measure.

Potential Impact on Implementation of Protective Ventilation

In this study, V_T was much higher when actual body weight rather than PBW was considered, which is in line with previous reports.[11] It is now recommended to set V_T based on PBW rather than actual body weight.[1,8,10] However, errors in the measurement or estimate of a patient's height are responsible for errors when calculating PBW and, consequently, V_T settings. It is likely that visual estimation is frequently used in mechanically ventilated patients. In the present study, the error in height estimation was greater in short subjects. Importantly, in this subgroup of shorter subjects, almost all were women. Consequently, the impact on V_T setting was greater in this subgroup. Patients of shorter height were less likely to receive protective ventilation in previous studies.[36,37]

The tape measure method was also associated with potentially high errors in V_T settings. Overestimation of V_T reached almost 150 mL when the tape measure method was used to calculate PBW rather than the reference height. With alternative methods (lower leg and forearm measurements), maximum errors in V_T were limited to between 73 and 87 mL. In addition, because of the formula for the PBW calculation, an error in height measurement or estimation leads to higher errors in V_T settings in women compared with men. (See the supplementary materials at http://www.rcjournal.com.) Our data help explain, in part, why women frequently receive higher V_T compared with men.[7,8,11,12,30,36]

These data highlight the importance of height in effectively reducing V_T, which may be difficult when accurate height measurements are not available. Consequently, finding an accurate and easy method to obtain height measurements in bedridden patients is of great importance.

Limitations

Our study has several limitations. The Chumlea method (based on lower leg measurement) was not recorded directly in bedridden subjects, but preoperatively in seated subjects with knees bent at a 90° angle, which limits the chance of errors. The results may therefore not be directly transposable to the situation of mechanically ventilated supine subjects. The present study is to be considered as a first step in assessing this method as a potential alternative

method of measurement. In a subsequent study, we evaluated a modified Chumlea method using lower leg measurement in bedridden subjects. Preliminary evaluation of this new method showed promising results, with very close correlation with the reference method.[38] In the present study, we did not test the reproducibility of the measurements with different investigators, and this will need to be performed in subsequent studies.

One must remember that the Chumlea stature prediction equations have been made specifically for defined populations[25] and that specific equations have been developed and should be used for differing populations.[39,40]

V_T may not be the optimum value to consider in mechanically ventilated patients. Indeed, some authors advocate the use of other physiologic surrogates, such as transpulmonary pressure or lung volumes, instead of V_T per PBW, given the variable effect of a unique value of V_T in a large population of subjects.[41]

Clinical Relevance

Protective mechanical ventilation is insufficiently implemented[19-23] due to several identified barriers; it is likely that difficulty in accurately measuring a subject's height and the lack of availability of derived formulas to calculate PBW are additional barriers. We described in this study several potential indirect methods that are at least as accurate as the tape measure method in bedridden subjects and that are more achievable. The data presented here also point out the inaccuracy of the visual estimation method, which can lead to large errors in V_T settings. Visual estimation of height should definitively be avoided, as well as the use of actual body weight to determine V_T.[10]

The optimum V_T to prevent[5,42] or treat[4] ARDS in mechanically ventilated patients is still not clearly defined. It is well accepted, however, that high V_T increases mortality in ARDS patients [1,4] and is associated with poor outcome in patients without ARDS.[5,6] To this end, implementation of low V_T strategies requires patients' heights to calculate PBW and to choose V_T based on PBW rather than on actual body weight. The formulas used in the present study have been implemented in a free smartphone application (iAnthropometer ICU) that may facilitate implementation of protective ventilation.[43]

Use of reliable methods to measure height is also desirable to homogenize practices in the clinical field and for research purposes. In a meta-analysis, Eichacker et al[4] showed that among the 5 randomized controlled trials evaluating different V_T values in ARDS subjects, 4 different methods were used to determine weight: actual weight, dry weight, ideal body weight, and PBW. These various surrogates of weight were acceptable when the rates of obesity (body mass index $> 30 \, \text{kg/m}^2$) were $\sim$10%, but today, these rates now approach nearly 40% in many countries,[44] and consequently, actual body weight cannot be used to set

the ventilator because of the risk of delivering high V_T.[8] In daily practice, the alternative methods that we describe may be more accurate than visual estimation and easier to apply in comparison with the tape measure method.

Conclusions

We showed that the method used to obtain a patient's height during mechanical ventilation might not be accurate and may have an impact on V_T settings. A V_T set according to actual body weight leads to large errors and should not be used; PBW requiring the patient's height should be used instead. The use of height measured with a tape measure, as well as visual estimation of height, can also lead to large errors in V_T settings. When reference height is not available in patients undergoing mechanical ventilation, alternative methods to obtain patients' heights based on lower leg and forearm measurements could be useful to facilitate the application of protective mechanical ventilation to prevent[5] or treat[1,2] ARDS. Knowledge and accurate application of a subject's height are low-cost therapeutic interventions based on basic physiology, as lung size is closely related to height.[9] This simple yet under-recognized fact should not be overlooked, especially if one considers that the only proven treatment of ARDS relies on the application of appropriate ventilatory settings.[1,2]

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