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The Accuracy of the Central Venous Blood Gas for Acid–Base Monitoring

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Abstract

Background: Routine use of central venous blood gases (VBGs) may reduce complications from prolonged arterial cannulation. We investigated the reliability of the VBG as a substitute for arterial blood gas (ABG) in multiple care settings. **Methods:** We developed a VBG adjustment rule of ABG pH = VBG pH + 0.05, ABG CO_2 = VBG P_{CO_2} −5 mm Hg from prior studies and validated this relationship with simultaneous venous and arterial blood obtained from 187 medical/surgical intensive care, cardiac catheterization laboratory, and coronary care unit patients with central venous access. **Results:** The overall accuracy of a normal adjusted VBG (aVBG) to predict a normal ABG was 90%. After adjustment, the mean systematic difference (bias) between ABG and VBG pH decreased from 0.035 ± 0.02 to −0.015 ± 0.02 and P_{CO_2} bias decreased from −4.5 ± 3.5 to 0.5 ± 3.5. Intraclass correlation coefficients for agreement improved after applying the adjustment rule to venous pH (from 0.84 to 0.93, $P < .001$) and P_{CO_2} (from 0.66 to 0.84, $P < .001$). Overall diagnostic accuracy of VBG improved from 45% to 74% after adjustment. Multiple logistic regression demonstrated that the factor independently associated with discrepancy between VBG and ABG diagnoses was an abnormal aVBG (OR 6.8, 95% CI 2.8-16.5). **Conclusions:** Because of the high agreement between a normal aVBG with a normal ABG and the small bias between these tests, we recommend use of the adjusted central VBG.

Keywords

blood gas analysis, monitoring, physiologic, acid–base equilibrium

Introduction

Arterial blood gas (ABG) testing is commonly used to determine oxygenation (P_{aO_2}) and acid–base status (pH, P_{CO_2} and HCO_3^-). Unfortunately, prolonged arterial catheterization is associated with rare, but serious, complications such as infection, bleeding, nerve injury, vascular injury, and limb loss.[1-4] Patients who require frequent blood gas testing often have indwelling central venous catheters for the administration of intravenous medications or the monitoring of central vascular pressures, allowing for repeated central venous blood gas (VBG) analysis. Given the reliability of continuous transcutaneous pulse oximetry for measurement of oxygenation,[4-7] multiple studies have looked to the VBG as a less invasive alternative for routine monitoring of acid–base status.[8-19] Despite demonstrating similar systematic differences (bias) between venous and arterial blood, these studies reached disparate conclusions regarding the reliability and accuracy of the VBG.[10-12,15,18] The purposes of this study were (1) to further describe the relationship between arterial and central VBGs, (2) to evaluate the accuracy of a central VBG adjusted to take into account the known systematic difference between venous and arterial blood, and (3) to identify clinical situations where the VBG might be an inaccurate surrogate for ABG.

Methods

Participants

This prospective comparison of venous and ABGs was conducted over the course of 2 months at a university-based, tertiary-referral, urban hospital. Consecutive patients older than 18 years admitted to the Coronary Care Unit, Medical Intensive Care Unit, Surgical Intensive Care Unit, or Cardiac

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Catheterization Laboratory with preexisting central venous access and a clinical need for both acid–base and chemistry determination were eligible for this study. Because no excess blood was drawn for the study and all data were stored in a deidentified database, informed consent was waived after review by the Hospital Institutional Review Board.

Specimen Collection

Arterial and VBGs were drawn simultaneously by the nurses caring for each eligible participant per the order of the primary physician. Arterial blood gases were drawn into heparinized syringes from radial or femoral arterial catheters and analyzed via the point-of-care Gem Premier 3000 system. The specimen was then sent for analysis to be used clinically via the hospital laboratory-based Bayer 865 system. Venous blood was drawn from central catheters—located in either the distal superior vena cava for intensive care unit (ICU) patients or the right atrium in cardiac catheterization laboratory patients—and sent for routine clinical analysis. No extra blood was drawn for study purposes; 0.1 mL of discard blood from specimens obtained for clinical care was processed for VBG analysis by respiratory therapists via the point-of-care Gem Premier 3000 system. This system was calibrated daily per manufacturer quality control protocols. Treating physicians were blinded to the results of the values from the Gem Premier 3000 system; these values were not used for patient care.

Venous Blood Gas-to-ABG Adjustment Rule

We developed a simple adjustment rule of ABG pH = VBG pH + 0.05 and ABG CO_2 = VBG P_{CO_2} − 5 mm Hg to "correct" for the previously described arteriovenous pH and P_{CO_2} differences in the critical care setting.[10-12,15,18] These adjustment equations were formulated through calculation of the weighted mean differences between arterial and venous pH and CO_2 from prior ICU-based studies of central venous blood.[10-12,15,18] Bicarbonate values were not adjusted.

Statistical Methods

The "agreement" between ABG and VBG or adjusted VBG (aVBG) was investigated with 3 statistical methods. The first method analyzed the P_{CO_2} and pH data as continuous values using Pearson correlations and intraclass correlation coefficients (ICCs) for absolute agreement.[20,21] Intraclass correlation coefficients combine measures of association and bias (systematic difference between measurements). This allowed for a statistical understanding of the relationships between ABG and VBG pH and P_{CO_2}, as well as an assessment of whether agreement between ABG and VBG improved after applying the adjustment formula. Second, Bland-Altman limits of agreement plots were constructed for these data. Limits of agreement plots visually represent the bias (mean difference) and variability (95% limits of agreement) between 2 methods of measurement.[19,22] Ninety-five percent limits of agreement were determined by 1.96 × standard deviation (SD) of the mean difference between ABG and VBG or aVBG values, as previously described by Bland and Altman.[13] R^2 was used to determine any relationship between the mean blood gas differences and the mean blood gas values to investigate any interaction between the ABG–VBG differences (bias) at the extremes of the blood gas values. Third, because ABG and VBG values are most useful in the context of clinical decision making, pH, CO_2, and HCO_3^- values were taken together to apply a standard blood gas diagnosis to each ABG and VBG (eg, "normal," "metabolic acidosis," "compensated respiratory acidosis," and so on). The diagnosis was assigned objectively through the application of standardized rules to a SAS data set, which then automatically generated a diagnosis. The rules used to obtain the diagnosis for each blood gas, as well as the distribution of ABG diagnoses, are shown in eTable 1. The normal ranges of CO_2, HCO_3^-, and pH from our hospital clinical laboratory were used to construct the diagnostic rules. Agreement between ABG and VBG clinical diagnoses was analyzed with κ statistics.

To determine whether the adjustment formula was the optimal method of transformation of the VBG, we compared the accuracy of VBGs derived from the adjustment rule to VBGs derived from the regression equations generated by our participant sample. These "regressed VBGs" would theoretically represent the optimal substitute for an ABG in this study population, though the equations may be clinically cumbersome and less generalizable to other populations than the prospectively determined adjustment rule.

The relationships between clinical variables measurable at the time of blood gas sampling (Table 3) and the concordance of aVBG-ABG diagnosis were first analyzed through odds ratios and Fisher exact tests (dichotomous variables) or Student *t* test (continuous variables). Variables reaching statistical significance ($P < .05$) in univariate analysis were included in multiple logistic regression analysis performed to determine which factors were independently associated with aVBG-ABG agreement. Statistical analyses were performed with SAS v9.3 (Cary, North Carolina) and Statistical Package for Social Sciences software (SPSS) v15.0.1 for Windows (Chicago, Illinois); ICC was calculated using the SPSS "2 way mixed" ICC for "agreement."[21]

Results

Simultaneous ABG and VBG data were available from 189 of 202 consecutive patients. Two patients were excluded due to likely ABG data entered incorrectly as VBG into the database (VBG $P_{aO_2} > 90$ on $F_{iO_2} < 0.40$ for both participants). The remaining 187 patients represent a wide range of patient care settings, diagnoses, and hemodynamic situations (Table 1).

The mean pH ± SD for ABG was 7.41 ± 0.07, VBG 7.37 ± 0.07, and aVBG 7.42 ± 0.07. For P_{CO_2}, ABG mean ± SD was 40 ± 6.3, VBG 45 ± 5.9, and aVBG 40 ± 5.9 mm Hg; and for HCO_3^- the mean for ABG was 25.4 ± 4.2 and VBG 26.6 ± 6.6 mmol/L. After applying the adjustment rule, the

Table 1. Baseline Participant Demographics

Total N = 187[a]	
Age (mean ± SD)	60.6 ± 13
Male sex N (%)	116 (66)
Intubated	60 (32)
Location N (%)	
Catheterization laboratory	105 (56)
CCU	45 (24)
MICU	26 (14)
SICU	9 (5)
Admitting diagnosis N (%)	
CAD	78 (59)
Pneumonia	28 (15)
Respiratory failure	21 (11)
Arrhythmia	18 (10)
COPD/asthma	16 (8.4)
Sepsis	16 (8.4)
Neurologic	12 (6)
Postoperative	10 (5)
Structural heart disease	10 (5)
ARDS	5 (2.6)
CHF	4 (2)
DKA	3 (1.5)
Participants requiring vasopressors	15 (8)
Hypotensive (MAP < 65)	12 (9)
Low venous 02 saturation (<65%)	56 (30)

NOTES: CAD = coronary artery disease; CCU = coronary care unit; CHF = congestive heart failure; COPD = chronic obstructive pulmonary disease; DKA = diabetic ketoacidosis; MICU = medical intensive care unit; SICU = surgical intensive care unit; SD = standard deviation.

[a] Total N reflects number of paired ABG–VBG results. Some categories with missing data points have lower N.

mean bias (systematic difference) between VBG and ABG pH decreased from 0.035 to −0.015 and the mean P_{CO_2} bias decreased from −4.5 to 0.5. The bias between ABG and VBG HCO_3 was −1.13 ± 4.8.

Scatterplots of ABG versus VBG values for pH and P_{CO_2} (Figure 1A and B, respectively) demonstrate the Pearson correlation coefficient of .95 for pH and .84 for P_{CO_2}. The regression formula for ABG versus VBG pH is ABGpH = 0.26 + 0.97 VBG P_{CO_2} and for ABG versus VBG P_{CO_2} is ABG P_{CO_2} = 0.29 + 0.89 VBG P_{CO_2}. The ICC coefficients significantly increase after VBG adjustment from 0.84 to 0.93 for pH and from 0.66 to 0.84 for P_{CO_2} (both comparisons between absolute ICCs, P < .001). Limits of agreement plots for comparison of ABG with aVBG data are shown in Figure 2A (pH) and Figure 2B (P_{CO_2}). The 95% limits of agreement were 0.027 to −0.057 for pH and 7.5 to −6.5 mm Hg for P_{CO_2}. No relationship was found between arteriovenous difference and extremes of blood gas values.

The diagnoses derived from ABGs were then compared to the diagnoses derived from VBGs and aVBGs (Table 2). The overall agreement between the unadjusted VBG diagnoses and the ABG diagnoses was 45% (κ .24, 95% CI 0.15-0.23). The VBG-to-ABG agreement significantly increased to 74% (κ .61, 95% CI 0.51-0.72) after adjustment of the VBG. The "regressed VBG" was 76% accurate (κ .64, 95% CI 0.55-0.73), which was not significantly different from our adjustment rule.

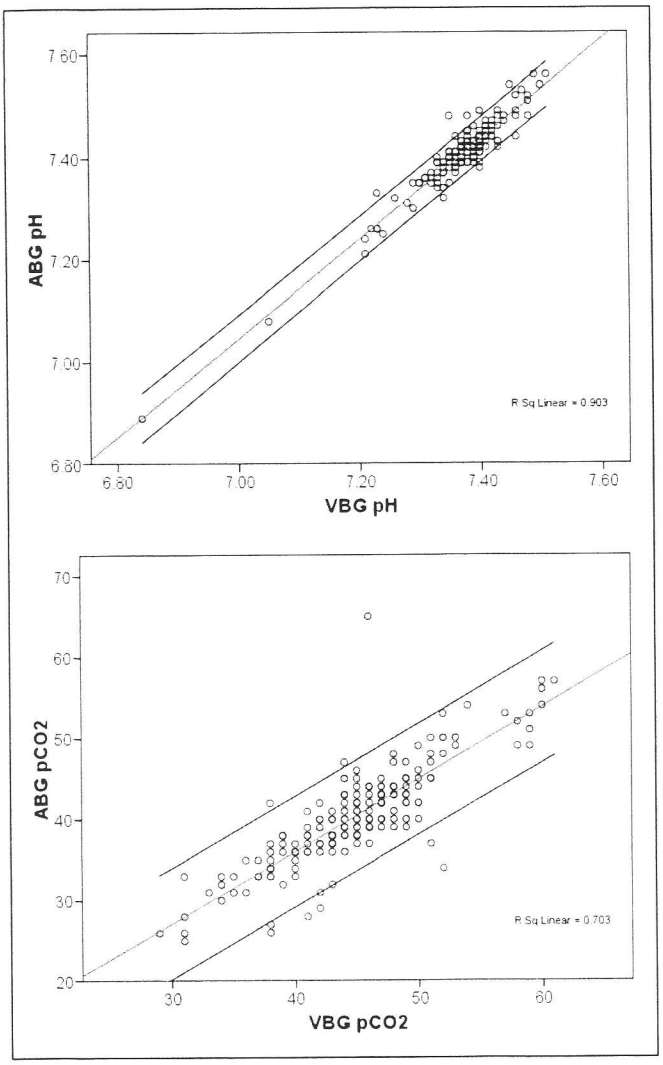

Figure 1. Scatterplots and regression equations for arterial blood gas (ABG) versus venous blood gas (VBG) pH and P_{CO_2}. Middle line represents regression line; parallel exterior lines represent 95% confidence intervals of regression line. A, pH. Scatterplot and regression equation for ABG and VBG pH. R^2 = .90. B, P_{CO_2}. Scatterplot and regression equation for ABG and VBG P_{CO_2}. R^2 = .70.

Univariate analyses showed that an abnormal aVBG diagnosis (P < .0001), a diagnosis of sepsis (P = .035), ICU location of care (.041), and female sex (.047) were associated with aVBG-ABG discordance (Table 3). Multiple logistic regression demonstrated that only an abnormal aVBG was independently associated with discordance with the ABG (OR 6.8, 95% CI 2.8-16.5, Hosmer-Lemeshow P = .28, R^2 = .23). A normal aVBG reached 90% agreement with the ABG diagnosis, whereas an abnormal aVBG matched the ABG diagnosis 58% of the time. No other variable was associated with discrepancy between ABG and aVBG. Although an abnormal aVBG predicted lack of agreement with the ABG, the arteriovenous bias and variability of pH and P_{CO_2} did not differ between normal and abnormal values (normal aVBG-ABG pH bias: −0.017 ± 0.020, abnormal pH aVBG-ABG bias: −0.014 ±

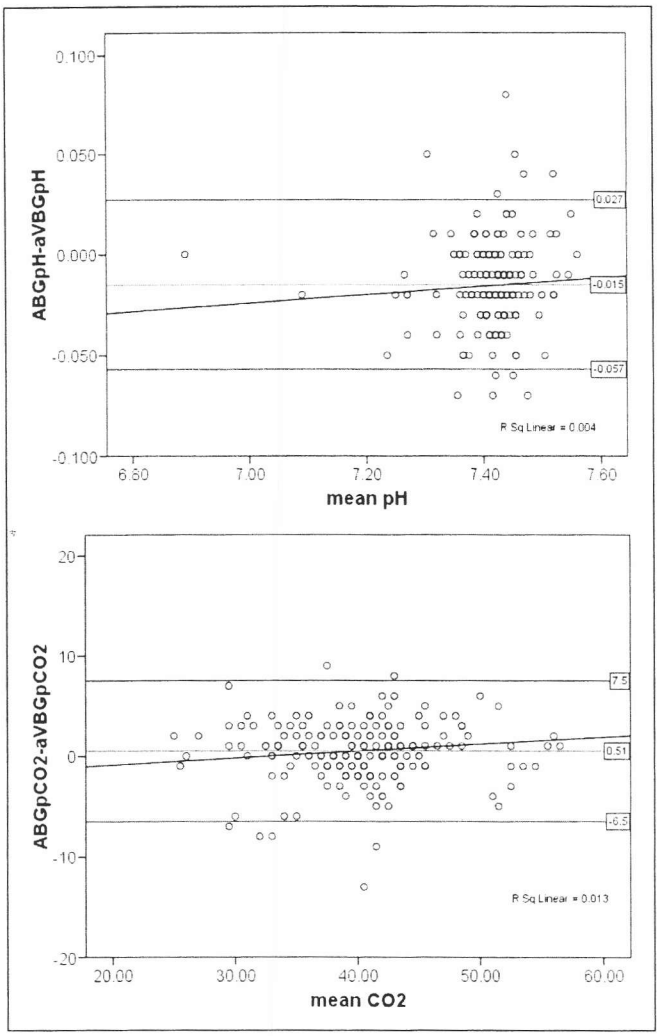

Figure 2. Bland-Altman limits of agreement plots for the comparison between arterial blood gas (ABG) and venous blood gas (VBG) pH and P_{CO_2}. Horizontal lines represent the mean bias between ABG and VBG values, parallel black lines represent the 95% limits of agreement. Diagonal lines represent correlation between the arteriovenous bias and the mean blood gas values. A, pH. Limits of agreement plot for the comparison between ABG pH and adjusted VBG pH. Bias between ABG and adjusted VBG pH −0.015, 95% limits of agreement 0.027 to −0.057. $R^2 = .004$. B, CO_2. Limits of agreement plot for the comparison between ABG CO_2 and adjusted VBG CO_2. Bias between ABG and adjusted VBG CO_2 is 0.5, 95% limits of agreement 7.5 to −6.5, $R^2 = .01$.

0.024, P = .28; normal P_{CO_2} aVBG-ABG bias: 0.34 ± 3.6, abnormal P_{CO_2} bias: 0.68 ± 3.4, P = .50). Therefore, as also demonstrated in the limits of agreement plots, arteriovenous pH and P_{CO_2} differences are similar between normal and abnormal ranges.

Discussion

Blood gases sampled from existing central venous catheters potentially represent a less invasive alternative to repeated ABG testing. We studied a large and diverse patient population to determine whether central venous and ABGs agree sufficiently to be interchangeable in clinical care. Additionally, this study prospectively validated a "VBG-to-ABG adjustment rule" intended to improve ABG–VBG agreement based on the previously described arteriovenous gradients for pH and P_{CO_2}.[10-12,15,18] Finally, we investigated which factors might predict instances when the VBG might be an inaccurate surrogate for ABG.

All statistical methods demonstrated significant improvement in the agreement between ABG and VBG values after applying the adjustment rule. Similar to prior studies into the relationship between the VBG and the ABG, we found a mean bias of 0.035 ± 0.02 between the ABG and the unadjusted VBG pH and a bias of −4.5 ± 3.5 mm Hg for unadjusted P_{CO_2} ABG-to-VBG comparisons. After applying the adjustment rules, mean bias decreased to −0.015 for pH and 0.5 mm Hg for P_{CO_2}, without a change in variability. Thus, it is clear that applying the VBG adjustment rule significantly reduces the bias (systematic difference) between these tests and significantly improves agreement between the aVBG and ABG.

Although improved statistical agreement, relatively high ICCs, and low bias for the aVBG suggest accurate clinical substitution, these statistical values do not directly answer the question of reliable clinical substitution. To determine whether substitution of the aVBG for ABG might be clinically reliable, we converted the blood gases into standard diagnostic categories (eTable 1). In addition, adjustment of the VBG increased overall accuracy of aVBG diagnosis from 45% to 74% (κ .61, 95% CI 0.51-0.72).

We then determined what clinical factors might predict the 26% of cases in which there was discordance between the aVBG and the ABG diagnoses. Multiple logistic regression analysis demonstrated that only an abnormal aVBG predicted discordance with ABG (OR 6.8, 95% CI 2.8-16.5). In contrast with the 90% agreement between a normal aVBG and a ABG, the agreement rate for an abnormal aVBG was 58%. Therefore, we propose that a normal aVBG is accurate for prediction of a normal ABG.

Although abnormal aVBGs less accurately matched the ABG diagnosis, we did not find any difference in the average arteriovenous bias or variability for the normal versus the abnormal ranges of pH, P_{CO_2}, and bicarbonate. Thus, though the adjustment rule was equally appropriate for normal and abnormal values of the actual component blood gas values (pH, P_{CO_2}), this did not translate into equal agreement of whole blood gas diagnostic categories. Because a unique diagnosis was given for any blood gas that had a pH, P_{CO_2}, or HCO_3- value that crossed any of the predefined "normal ranges," lack of agreement could be seen for participants with arteriovenous pH differences of as little as 0.01 or P_{CO_2} differences of 1 mm Hg. For example, a pH of 7.34 would lead to different blood gas diagnosis compared with a pH of 7.35, though it is unclear whether this difference would result in a change in care. In fact, of the 39 abnormal aVBGs, only 9 had arteriovenous pH values with differences greater than 0.03. In addition, as is shown in Table 3, the majority of "abnormal"

Table 2. Agreement Between Adjusted Central Venous Blood Gas Diagnoses and Arterial Blood Gas Diagnoses[a]

		Adjusted VBG Diagnosis									
	Diagnosis	Normal	Resp Acidosis	Resp Alkalosis	Met Acidosis	Met Alkalosis	Comp Resp Acidosis	Comp Met Acidosis	Comp Resp Alkalosis	Comp Met Alkalosis	Mixed
ABG diagnosis	Normal	**85**	0	2	1	0	0	0	0	0	13
	Resp acidosis	0	**3**	0	0	0	0	0	0	0	1
	Resp alkalosis	2	0	**7**	0	0	0	0	0	0	2
	Met acidosis	0	0	0	**1**	0	0	0	0	0	1
	Met alkalosis	0	0	0	0	**8**	0	0	0	0	1
	Comp resp acidosis	0	0	0	0	0	**4**	0	0	3	2
	Comp met acidosis	0	0	0	0	0	0	**2**	0	0	0
	Comp resp alkalosis	1	0	0	0	0	0	0	**1**	0	1
	Comp met alkalosis	0	0	0	0	2	0	0	0	**4**	1
	Mixed	7	0	4	2	2	0	0	0	1	**23**
	Total	95	3	13	4	12	4	2	1	8	45

NOTES: ABG = arterial blood gas; comp = compensatory; met = metabolic; resp = respiratory; VBG = venous blood gas.
[a] Bold indicates adjusted VBG and ABG agreement.

Table 3. Univariate Analysis and Multiple Logistic Regression Analysis of Factors Associated With a Discrepancy[a]

Variable	Univariate OR (95% CI); *P* Value	Multivariate OR (95% CI); *P* Value
Adjusted VBG normal: no versus yes	**6.3 (2.9, 13.6); <.0001**	**6.8 (2.8, 16.5); <.001**
Sepsis diagnosis: no versus yes	**0.32 (0.11, 0.90); .035**	0.25 (0.06, 1.07); .06
Site of care: Catheterization Laboratory versus ICU	**0.48 (0.25, 0.94); .041**	1.33 (0.58, 3.09); .50
Sex: female versus male	**2.04 (1.02, 4.09); .047**	1.45 (0.66, 3.17); .35
Mechanical ventilation: no versus yes	0.59 (0.30, 1.17); .15	N/A
Venous O_2 saturation <65%: no versus yes	1.10 (0.54, 2.27); .86	N/A
Cardiac diagnosis: no versus yes	1.48 (0.77, 2.85); .25	N/A
Pulmonary diagnosis: no versus yes	0.71 (0.33, 1.52); .42	N/A
Hypotensive MAP < 65 mm Hg: no versus yes	0.85 (0.25, 2.87); .76	N/A
Vasopressor requirement: no versus yes	0.97 (0.30, 3.22); 1.0	N/A

NOTES: ABG = arterial blood gas; ICU = intensive care unit; MAP = mean arterial pressure; VBG = venous blood gas.
[a] Cardiac diagnoses include coronary artery disease, arrhythmia, structural heart disease, congestive heart failure; pulmonary diagnoses include pneumonia, chronic obstructive pulmonary disease/asthma, acute respiratory distress syndrome, respiratory failure;. Between adjusted VBG- and ABG-derived acid–base diagnoses. Bold indicates statistically significant with $P < .05$. Only analyses with $P < .05$ were included in the multiple logistic regression analysis (under multivariate OR).

blood gases fell into the "mixed" diagnosis range. This category is expected to yield the least accurate diagnosis because further information such as an anion gap, which was not available from our data set, was necessary to determine the correct acid–base disturbance. Given the minority of participants who had abnormal blood gases and the high rate of complex "mixed" acid–base disturbances among these, further study is necessary to draw any conclusions regarding the clinical utility of abnormal aVBGs.

To our knowledge, this is the first study to validate the proposal by Steinberg and Harken,[12] that adjusting the VBG pH and P_{CO_2} may allow substitution for an ABG. The simple formula of ABG pH = VBG pH +0.05 and ABG P_{CO_2} = VBG P_{CO_2} −5 mm Hg has the advantage of ease of use, and similar accuracy, compared with regression equations. In smaller and more homogeneous populations, Phillips and Peretz[10] and Malinoski et al[18] proposed that central venous pH and P_{CO_2} can be reliably substituted for their ABG analogs only when the VBG values are normal. Our study also demonstrated that the diagnostic agreement between these tests is best when the aVBG is normal. Because of the high agreement between aVBG and ABG in the "normal" range, we can recommend use of the aVBG in patients with indwelling central venous catheters in a recovery or ventilator weaning phase of critical illness. This practice has the potential to reduce the complication rate associated with long-term arterial catheterization.

As previously stated, limits of this study include a small proportion of patients with abnormal pH and P_{CO_2} values. Further study of differences in clinical decision making based on aVBGs from a patient population with a high pretest likelihood of abnormal blood gases is necessary before recommending routine use of an abnormal aVBG. However, the range of surgical, medical, cardiac ICU and cardiac catheterization patients studied does allow for the generalization of our findings to a wide range of care settings. We did not investigate, and thus cannot recommend, use of the peripheral VBG, which in past studies in the critical care setting has shown greater bias and unpredictability than central venous blood.[13] Finally, a clinical trial comparing central VBG to ABG utilization strategies would be necessary to determine whether routine central VBG use decreases complication rates in the critical care setting.

In conclusion, adjusting the VBG pH up by 0.05 and P_{CO_2} down by 5 mm Hg significantly improves the agreement between the central venous and ABG. This adjustment allows for the reliable and less-invasive prediction of a normal ABG from a normal adjusted central VBG. Although the abnormal aVBG was less accurate in predicting the ABG diagnosis, it is unclear whether the small absolute arteriovenous pH and P_{CO_2} differences would result in changes in clinical care. Further study of the accuracy of abnormal VBGs is warranted.

Declaration of Conflicting Interest

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Appendix

Blood Gas Ranges	Diagnosis	ABG Count
pH 7.35-7.45 PCO_2 35-45 mmHg HCO3- 21-28 mmol/L	Normal	101
pH <7.35 PCO_2 >45 mmHg HCO3- 21-28 mmol/L	Respiratory acidosis	4
pH >7.45 PCO_2 <35 mmHg HCO3- 21-28 mmol/L	Respiratory alkalosis	11
pH <7.35 PCO_2 35-45 mmHg HCO3- <21 mmol/L	Metabolic acidosis	2
pH >7.45 PCO_2 35-45 mmHg HCO3- >28 mmol/L	Metabolic alkalosis	9
≥7.35 pH ≤ 7.40 PCO_2 > 45mmHg HCO3- >28 mmol/L	Compensated respiratory acidosis	9
≥7.35 pH ≤ 7.40 PCO_2 <35 mmHg HCO3- <21 mmol/L	Compensated metabolic acidosis	2
≥7.40 pH ≤ 7.45 PCO2 < 35mmHg HCO3- <21 mmol/L	Compensated respiratory alkalosis	3
≥7.40 pH ≤ 7.45 PCO_2 > 45mmHg HCO3- >28 mmol/L	Compensated metabolic alkalosis	7
If none of the above applies	Mixed disorder	39

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