Acid–Base Analysis in the Operating Room: A Bedside Stewart Approach

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All models are wrong but some are useful.

—George Box, British statistician, 1976

Most patients receiving anesthesia care have some care-driven changes in their acid–base status, at least mild respiratory acidosis during general anesthesia with spontaneous ventilation. However, many high-risk patients also have clinically important acid–base changes that anesthesiologists need to interpret and manage, often actual or impending metabolic acidosis and acidemia.[1] These clinical situations can be challenging. Anesthesiologists' concerns include the nature and clinical importance of acid–base changes, the underlying causes, the likely effects of interventions including fluid therapy and sodium bicarbonate, perioperative risk, and need for postoperative intensive care unit (ICU) admission (refer to examples 1 to 4 in Boxes 1 to 4).

Most anesthesiologists are familiar with the fundamental blood gas machine acid–base measurements of pH and pCO_2, and derived bicarbonate concentration, all linked by the Henderson–Hasselbalch equation.[2–4] Many will use or be aware of base excess,[4] and some the physicochemical (Stewart) approach.[2] Understanding acid–base physiology and disorders can be complicated and often discouraging due to extensive physiologic descriptions of simultaneous changes in physical chemistry including equilibria, electroneutrality, transmembrane electrolyte and fluid shifts, Gibbs–Donnan effects, physiologic respiratory and nonrespiratory (metabolic) compensation, and the effects of associated disease and procedures.[2,5] While pH, or better hydrogen ion concentration, determines the severity of the acid–base adverse effects on protein structure and function,[6] acid–base changes are often of secondary clinical importance to the adverse effects of the underlying cause of the acid–base changes; two important examples are sepsis and hypovolemic shock.[7,8] Unfortunately, clinician certainty about acid–base analysis is further undermined by persisting, and remarkably colorful, disagreements between experts about the preferred approach to acid–base—bicarbonate, base excess, or Stewart—although there is considerable overlap between the three (table 1, examples 1 to 4 in Boxes 1 to 4).[2,7,9] No one has yet devised a study that can definitively determine whether the bicarbonate or Stewart approach is more valid for clinical use. However, an example of added benefit is that the Stewart approach can explain the phenomenon of increased plasma bicarbonate concentration associated with decreased plasma albumin concentration: alkalosis secondary to decreased plasma weak acids. In contrast, bicarbonate-based approaches cannot easily explain this inverse relationship between plasma albumin and bicarbonate despite advocates recommending correcting the anion gap for decreased albumin.[10] Further, studies of ICU patients, including postoperative patients, conclude that the Stewart approach can be superior in detecting important acid–base changes despite patient pH being in the reference range (7.35 to 7.45)[11–13] and no apparent acid–base disorder using bicarbonate or base excess analysis (example 4 in Box 4). In this review focusing on clinical anesthesia, I am proposing a simplified Stewart approach that incorporates base excess because it is associated with greater insight into the underlying causes including some masked by other processes.[13,14] Importantly, there is no evidence that any contemporary approach to diagnosing acid–base disorders is superior to others in improving patient outcomes.

For anesthesiologists, the inverse relationship between the alveolar minute ventilation and arterial partial pressure of carbon dioxide is a scientific foundation of practice. However, on the metabolic (nonrespiratory) side of acid–base analysis, there is less clarity.[2,9] The dominant approach that evolved in the second half of the twentieth century uses plasma bicarbonate concentration as both the primary marker and the primary determinant of metabolic acid–base status[2] relative to any changes in the partial pressure of carbon dioxide (table 1). Textbooks describe complex renal physiology reclaiming, creating, or excreting bicarbonate.[9,15] An alternative paradigm named after physiologist Peter Stewart[16,17] has much to offer anesthesiologists but needs to be simplified to be user-friendly for perioperative patient care.[2,7,18]

In the opening quotation about models of natural phenomena, when George Box said[19] that all models are wrong, he meant that models cannot completely describe natural phenomena, and he called for "simple but evocative

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Table 1. Primary Acid–Base Disorders and Expected Physiologic Compensation Changes, Modified from Berend 2018[7]

Primary Disorder	Using SBE	Using Bicarbonate
Acute respiratory acidosis	SBE = 0	HCO_3^- = 24 + 0.1 × ($Paco_2$ - 40)
Acute respiratory alkalosis	SBE = 0	HCO_3^- = 24 + 0.2 × ($Paco_2$ - 40)
Chronic respiratory acidosis	SBE = ($Paco_2$ - 40)/3	HCO_3^- = 24 + 0.35 × ($Paco_2$ - 40)
Chronic respiratory alkalosis	SBE = ($Paco_2$ - 40)/3	HCO_3^- = 24 + 0.5 × ($Paco_2$ - 40)
Metabolic acidosis	$Paco_2$ = 40 + SBE	$Paco_2$ = 1.5 × (HCO_3^-) + 8
Metabolic alkalosis	$Paco_2$ = 40 + SBE/2	$Paco_2$ = 0.9 × (HCO_3^-) + 9

*±5 mmHg for respiratory compensation for metabolic changes; and ±2.5 mM for bicarbonate and base excess compensation for respiratory changes.
mM = mmol/l; SBE, standard base excess.

models." There is no doubt that the natural phenomena of acid–base physiology in health and disease are complex[5] and lead to degrees of confusion and even disinterest for many clinicians. This model to assess the nonrespiratory side of acid–base is simple, but evocative, and was developed with anesthesiologists and other critical care clinicians in mind.[20,21] It is not definitive or all-inclusive but appears useful (examples 1 to 4 in Boxes 1 to 4).

Clinical Metabolic Acid–Base Diagnosis

Clinical acid–base analysis is defined by changes from a "normal point": pH, 7.40; $Paco_2$, 40 mmHg; bicarbonate, 24 mM; and base excess, 0 mM. However, vital to the beside Stewart model, also at this pH 7.40 point are plasma sodium, 140 mM; chloride, 105 mM; lactate, 1.0 mM; and albumin, 42 g/l, the middle of the reference ranges. The bicarbonate-centered approach to acid–base analysis has limited overlap with routinely measured electrolytes, except when estimating the anion gap, traditionally Na–Cl–HCO_3.[7,22] The Henderson-Hasselbalch equation can lead to confusion because it is used to represent both (1) the physical chemical equilibria of carbonic acid in solution and (2) physiologic regulation of bicarbonate and carbon dioxide, predominantly through renal and respiratory mechanisms.[2] Further, the bicarbonate-based approaches to acid–base diagnosis are largely categorical (yes or no) and require accounting for physiologic changes in carbon dioxide using rules of thumb to determine if there is physiologic respiratory compensation (table 1).[2,7] The bicarbonate-based approaches do not routinely quantify metabolic derangements and therefore do not routinely estimate the severity of metabolic disorders. While the anion gap helps determine whether there may be pathologic anions during metabolic acidosis (examples 1 and 3 in Boxes 1 and 3), this is usually categorical—raised anion gap acidosis: yes or no?[22]

Base excess[4] was introduced more than half a century ago to readily separate metabolic acid–base disorders from respiratory disorders and quantifying their severity by modeling changes when blood is equilibrated with an atmosphere with a pCO_2 of 40 mmHg, effectively removing any respiratory change.[7] Standard base excess (SBE), also known as the base excess of extracellular fluid, is more physiologically sound than the original actual base excess,[7] which unfortunately is still often reported. Base excess represents the number of millimoles of strong base (NaOH) for negative base excess or strong acid (HCl) for positive base excess added to a liter of plasma to return pH to 7.40 where the pCO_2 in plasma is 40 mmHg at 37°C. Blood gas machines calculate base excess using the Van Slyke equation. The base excess reference range is approximately −2.5 to +2.5 mM. Although base excess was introduced long ago, many clinicians continue to prefer bicarbonate-based approaches[22] despite the relative simplicity and clinical value of base excess in quantifying, rather than only classifying, metabolic acid–base changes.[7] A recent excellent review describes clinical use of base excess in detail.[7] Base excess has simpler equations for changes of carbon dioxide physiologic compensation than bicarbonate approaches (table 1).

Peter Stewart[23] never directly addressed base excess but opened his 1978 acid–base publication[17] with, "Acid-base solution chemistry is an emotionally charged area of science, partly because of the frustrations we have all experienced in trying to master it." Stewart proposed that the hydrogen ion concentration is an important physiologic variable but that is dependent on other factors, and that bicarbonate is unimportant mechanistically and is also dependent on other factors.[16,23]

As with both bicarbonate and base excess approaches, the Stewart-derived approaches[7,18,21] analyze the partial pressure of carbon dioxide as the central component of the respiratory side of acid–base status. However, in the Stewart approach, the nonrespiratory (metabolic) factors for biologic solutions including plasma and adjoining extracellular fluid are (1) the strong ions that are completely dissociated and (2) weak acids that are only partly dissociated anions and so exist as undissociated acids, anions, and hydrogen ions in equilibrium ($HA \leftrightarrow A^- + H^+$). The key controlling elements are (1) the difference between the concentrations of the strong positive cations and the strong negative anions—the strong ion difference—with acidosis when the strong ion difference is decreased and alkalosis when the strong ion difference is increased; (2) the total amount of weak acid ($HA + A^-$) with acidosis from increased total weak acids and alkalosis from decreased total weak acids;

Box 1. Combined Metabolic Acidoses (Example 1)

43-yr-old previously well patient with abdominal sepsis undergoing laparotomy following initial saline resuscitation: pH 7.25, $Paco_2$ 35 mmHg, bicarbonate 14.8 mM, base-excess -11.0 mM, sodium 142 mM, chloride 112 mM, lactate 4.5 mM, and albumin 32 g/l.

Bicarbonate centered

1) Metabolic acidosis
2) Expected compensated $Paco_2$ (mmHg) equals 1.5 × Bicarbonate + 8
   = 30.2 ± 5 (actual 35)

Conclusion: Mixed disorder with metabolic acidosis and possible relative respiratory acidosis

Albumin corrected anion gap (mM)
= 142 – 112 – 14.8 + 0.25 × (42 -32) = 17.7

Conclusion: Mixed disorder with wide anion gap metabolic acidosis and relative respiratory acidosis

Base-excess

1) Metabolic acidosis
2) Expected compensated $Paco_2$ (mmHg) equals 40 + base-excess change
   = 29 ± 5 (actual 35)

Conclusion: Mixed disorder with metabolic acidosis and relative respiratory acidosis

Albumin corrected anion gap (mM)
= 142 – 112 – 14.8 + 0.25 × (42 – 32) = 17.7

Conclusion: Mixed disorder with wide anion gap metabolic acidosis and relative respiratory acidosis

Bedside Stewart

Base-excess diagnosis

1) Metabolic acidosis
2) Expected compensated $Paco_2$ (mmHg) equals 40 + base-excess change
   = 29 ± 5 (actual 35)

Conclusion: Mixed disorder with metabolic acidosis and relative respiratory acidosis

3) Further chloride and lactate (strong anions) above reference range and albumin (weak acid) below reference range

Effects on SBE
Na-Cl effect (mM) = 142 – 112 – 35 = -5
Albumin effect (mM) = 0.25 × (42 – 32) = +2.5
Lactate effect (mM) = 1 – 4.3 = -3.3
Other-ion effect (mM) = -11 + 5 – 2.5 + 3.3 = -5.2

Added conclusion: Metabolic acidosis due to combined effects of relative hyperchloremic acidosis, lactic acidosis, and other-ion acidosis, all partly offset by hypoalbuminemic alkalosis.

Possible actions to consider in the operating room: (1) avoid further saline by switching to lower chloride fluids; (2) intravenous sodium bicarbonate (chloride free sodium) therapy; (3) increase alveolar minute ventilation, particularly if sodium bicarbonate administered; (4) anticipate postoperative Intensive Care Unit admission including mechanical ventilation; and (5) avoid giving intravenous albumin fluids.

SBE, standard base excess.

Box 2. Masked Other Ion Acidosis (Example 2)

65-yr-old patient with chronic obstructive pulmonary disease without hypercapnia, diabetes, severe chronic kidney disease, and leg ischaemic for peripheral arterial surgery. First intraoperative arterial blood gas.

pH 7.34, $Paco_2$ 47 mmHg, Bicarbonate 24.5 mM, SBE -0.8 mM, Na 148 mM, Chloride 114 mM, Lactate 0.7 mM, Albumin 22 g/l.

Bicarbonate centered

1) Respiratory acidosis
2) Expected compensated bicarbonate (mM) equals 24 + 0.1 × ($Paco_2$ - 40)
   = 24.7 ± 2.5 (actual 24.5)

Conclusion: Compensated respiratory acidosis

Base-excess

1) Acute respiratory acidosis
2) Expected compensated SBE (mM) equals 0
   = 0 ± 2.5 (actual -0.8)

Conclusion: compensated respiratory acidosis

Bedside Stewart

1) Respiratory acidosis
2) Expected compensated SBE (mM) equals 0
   = 0 ± 2.5 (actual -0.8)
3) But sodium and chloride (strong ions), and albumin (weak acid) outside reference ranges.

Effects on SBE
Na-Cl effect (mM) = 148 – 114 – 35 = -1
Albumin effect (mM) = 0.25 × (42 – 22) = +5
Lactate effect (mM) = 1 – 0.3 = +0.7
Other-ion effect (mM) = -0.8 – 1- 5 – 0.7 = -5.1

Added Conclusion: Respiratory acidosis with other-ion acidosis offset by severe hypoalbuminemia giving the incorrect impression of a physiologically compensated primary respiratory acidosis. Despite hyperchloremia there is no significant hyperchloremic metabolic acidosis due to hypernatremia maintaining the strong-ion-difference.

Possible actions to consider in the operating room: (1) avoid high chloride fluids; (2) revise risk assessment given this high-risk patient has marked metabolic abnormalities revealed by the Stewart approach that indicates this patient is sicker and possibly at greater risk of perioperative mortality and morbidity than based on initial assessment; and (3) discuss with perioperative medicine team who may not be aware of degree of metabolic abnormality.

SBE, standard base excess.

and (3) temperature-dependent dissociation constants for the weak acids.[7,18,21] The key components of plasma clinical chemistry in health and disease and drivers of acid–base status are the sodium, chloride, and lactate strong ions, and the amino acid weak acids in albumin. Bicarbonate and pH are dependent on these factors and the partial pressure of carbon dioxide, with hydrolysis of water being the primary hydrogen ion source (examples 1 to 4 in Boxes 1 to 4).

Box 3. Iatrogenic Acidosis from Chloride and Albumin (Example 3)

Patient who has had plasmapheresis for a metabolic disorder before surgery including replacement with 5% albumin (50 g/l albumin, Na 150 mM, Cl 130 mM).

pH 7.35, $Paco_2$ 35 mmHg, Bicarbonate 18.1 mM, SBE -6.5 mM, Sodium 145 mM, Chloride 115 mM, Lactate 0.5 mM, Albumin 48 g/l.

Bicarbonate centered

1) Metabolic acidosis
2) Albumin corrected anion gap, mM
   = 145 – 115 -18.1 + 0.25 × (42 – 48) = 10.4
3) Expected compensated $Paco_2$ (mmHg) equals 1.5 × Bicarbonate + 8
   = 35.2 ± 5 (actual 35mmHg)

Conclusion: compensated narrow anion gap metabolic acidosis

Base-excess

1) Metabolic acidosis
2) Albumin corrected anion gap, mM
   = 145 – 115 -18.1 + 0.25 × (42 – 48) = 10.4
3) Expected compensated $Paco_2$ (mmHg) equals 40 + SBE
   = 33.5 ± 5 (actual 35 mmHg)

Conclusion: compensated narrow anion gap metabolic acidosis

Bedside Stewart

1) Metabolic acidosis
2) Respiratory compensation
3) But both chloride (strong anion) and albumin (weak acid) above reference range

   Na-Cl effect (mM) = 145 – 115 - 35 = -5.0
   Albumin Effect (mM) = 0.25 × (42 – 48) = -1.5
   Lactate effect (mM) = 1 – 0.5 = +0.5
   Other ions (mM) = -6.5 + 5 + 1.5 – 0.5 = -0.5

Added conclusion: relative hyperchloremic acidosis with added acidosis from hyperalbuminemia, both consistent with 5% albumin therapy.

Possible actions to consider in the operating room: (1) have greater confidence that metabolic acidosis is unlikely to reflect metabolic dysfunction and increased perioperative risk; (2) avoid saline; and (3) anticipate the acidosis will resolve with more physiological fluids in the perioperative period.

SBE, standard base excess.

Box 4. Persisting Acidoses after Bicarbonate Therapy (Example 4)

Mechanically hyperventilated patient with previous metabolic acidosis treated with 0.125% (150 mM) intravenous sodium bicarbonate therapy.

pH 7.46, $Paco_2$ 35 mmHg, Bicarbonate 25 mM, SBE +1.3 mM, Na 143, Chloride 99, Albumin 32, Lactate 6.2 mM.

Bicarbonate centered

1) Acute respiratory alkalosis
2) Expected compensated bicarbonate equals 24 + 0.2 × ($Paco_2$ - 40)
   = 23 ± 2.5 (actual 25)

Conclusion: Compensated respiratory alkalosis

Base-excess

1) Respiratory alkalosis
2) Expected compensated SBE (mM) equals 0
   = 0 ± 2.5 (actual + 1.3)

Conclusion: Compensated respiratory alkalosis

Bedside Stewart

1) Acute respiratory alkalosis
2) Expected compensated SBE (mM) equals 0
   = 0 ± 2.5 (actual +1.3)

Initial Conclusion: Respiratory alkalosis with minimal SBE change

3) But chloride, lactate, and albumin outside reference ranges.

Effects on SBE
   Na-Cl effect (mM) = 143 – 99 – 35 = +9 mM
   Albumin effect (mM) = 0.25 × (42 – 32) = +2.5 mM
   Lactate (mM) = 1.0 – 6.2 = -5.2 mM
   Other ions (mM) = 1.3 – 9 - 2.5 + 5.2 = -5.0 mM

Conclusion: Important lactic and other-ion acidoses masked by hypoalbuminemic alkalosis and relative hypochloremic alkalosis due to both decreased chloride and increased sodium from dilute sodium bicarbonate therapy, 1.26% (150 mM).

Possible actions to consider in the operating room: (1) Decrease alveolar minute ventilation; (2) assume likely increased risk of postoperative mortality due to lactic acidosis and other ion acidosis, masked by hypoalbuminemia and iatrogenic relative hypochloremic alkalosis; and (3) anticipate theses acidoses may worsen.

SBE, standard base excess.

The Stewart acid–base approach challenges the mainstream bicarbonate paradigm and is viewed by some as almost heretical.[10] Unfortunately, limitations of Stewart's original work include underreferencing, unfamiliar ideas such as strong ion difference, and an intimidating fourth-order polynomial equation derived from six simultaneous equations that combines all the factors to describe acid–base status in a fluid compartment, which is unsuitable for easy clinical application.[2] In line with concepts proposed George Box, the aim of our group and others[14,24] has been to develop a simplified Stewart model that, while not fully physiologically correct, is clinically useful.

Simplified Stewart Acid–Base Model

Assessing primary respiratory changes or expected respiratory compensation is applied in similar ways across bicarbonate-centered, base excess, and Stewart approaches

(table 1, examples 1 to 4 in Boxes 1 to 4). Early approaches to simplifying the Stewart acid–base approach[2,7,16,18,24] combined base excess as an overall metabolic acid–base metric with changes in sodium and chloride as the principal plasma strong ions and albumin as the principal plasma nonvolatile weak acid. They examined sodium and chloride effects on base excess in two separate equations and referred to changes in free water indicated by changes in sodium concentration and chloride corrected for measured sodium relative to 140 mM. This has problems: (1) the concept of free water excess or deficit is not particularly useful or familiar in clinical anesthesia[25,26]; (2) the importance of the *difference* between sodium and chloride concentrations is hidden; (3) this approach requires two calculations that most would require a calculator to perform; (4) even recent versions do not asses the effect of lactate if measured;[14] and (5) the calculated acid–base effect of changes in albumin using the formula [albumin] × (0.123 × pH – 0.631) which is unnecessarily complex for clinical use[7,27] and can be simplified to 0.25 × [42 – measured albumin, g/l] for a reasonable approximation.[20,28]

Residual base excess effects are attributed to other ions, usually anions.[14] The anion gap when corrected for albumin is a closely related chemical construct (examples 1 and 3 in Boxes 1 and 3).[27] Other ions are common among critically ill and high-risk surgical patients. In the past, these other ions included lactate.[8,20] With advances in point-of-care blood gas analyzers, plasma lactate measurements are now often routinely available, along with sodium and chloride. There is good evidence that increasing plasma lactate concentration is associated with increasing mortality among patients admitted to ICU, including those admitted from the operating room.[8,29,30] Quantitatively assessing extent of any lactic acidosis from venous or arterial blood gasses should be routine for perioperative patients.[8,22,30] Beyond lactate, the effects and importance of other ions are an area of scientific uncertainty, with some evidence for associations with mortality.[21,28,29]

Simple Stewart for the Operating Room

Our group started with the previous approaches combining base excess[28] and elements of the Stewart approach to create a simplified Stewart approach to analyzing metabolic acid–base changes. Our aim was to create a simple pragmatic bedside approach particularly for managing high-risk or critically ill perioperative patients, and those receiving large volumes of intravenous fluid therapy (examples 1 and 3 in Boxes 1 and 3). Like others, we used SBE[7,18,24] as the overall metric for metabolic acid–base status and then analyzed the quantitative effects on base excess of important routinely measured independent elements controlling the metabolic (nonrespiratory) acid–base status in plasma: the strong ion difference (sodium–chloride–lactate) and total weak acids (albumin).[7,20,21] The residual base excess effects from other ions included ions that could be measured, such as ketones or phosphate, or other strong ions or weak acids ions not routinely measured in clinical chemistry. The associated assumed set points for the strong ions and weak acids are commonly used medians of the reference range for each of these elements (sodium, chloride, lactate, and albumin),[7,21,31] but may vary with analyzers and populations.

Therefore, the acid–base starting "normal point" is as follows: pH 7.40, pCO_2 40 mmHg, bicarbonate 24 mM, base excess 0 mM, sodium 140 mM, chloride 105 mM, lactate 1.0 mM, and albumin 42 g/l. Acid–base analysis centers on changes in these variables from this ideal point.

In summary, the most recent version of our approach,[21] is

Standard base excess (SBE) mM =
SBE effect of sodium - chloride [Na –Cl – 35]
(strong ions)
+ SBE effect of lactate [1- lactate]
(strong anion)
+ SBE effect of albumin [0.25 X (42- albumin, g/L)]
(weak acid)
+ SBE effect of other ions
(strong ions, weak acids, weak bases)

This assumes that lactate is measured; otherwise, the older version can be used.[2]

Aids to Using Stewart in the Operating Room

After we updated our simplified Stewart approach to quantitively analyzing acid–base disorders to routinely include lactate and changes in chloride reference ranges,[20,21] John Friesen, M.D., from University of Manitoba, Winnipeg, Canada, reported[31] turning this simplified Stewart approach into a web application (https://www.abgst.altervista.org/) to further aid bedside use of this approach. The help section of the web application also references important acid–base equations.

As a further contribution to a simple bedside approach, an anesthesiologist from India (Anitha Nileshwar, M.B.B.S., M.D., Department of Anesthesiology, Kasturba Medical College, Manipal, India, personal communication, November 2020, email) devised the mnemonic SALT for the elements of the bedside Stewart approach:

S = **S**odium − chloride base excess effect
A = **A**lbumin base excess effect
L = **L**actate base excess effect
T = **T**rash ions (o**T**her ions) base excess effect

Therefore, base excess = S + A + L + T, an easy-to-remember summary of plasma metabolic acid–base status.

Other Ions

Lactate and other ions fill a widened anion gap,[7,29] and acid–base changes related to these ions are associated with worse outcome in critically ill patients than similar acid–base changes associated with sodium−chloride and albumin.[20,29] When we first described our version of a simplified Stewart approach,[20] lactate was not a routine clinical measurement. In the subsequent update, we modified the simplified Stewart approach to include lactate.[21] However, it is likely that there is a large array of other ions (examples 1, 2, and 4 in Boxes 1, 2, and 4) from organ dysfunction, cellular injury, disturbed metabolism, and exogenous poisoning.[8] A new source of other ions is euglycemic ketoacidosis associated with patients with diabetes taking sodium glucose on cotransporter 2 inhibitors (SGLTIs)[32] and is an increasingly important differential diagnosis now that these drugs have indications beyond diabetes care.[33]

Hypoalbuminemia

Albumin lies at an intersection of the Stewart and bicarbonate approaches. Many use the anion gap ($Na–Cl–HCO_3$) to qualitatively detect other anions during metabolic acidosis.[7] Like the Stewart approach, the anion gap relies on the principle of plasma electroneutrality: sum of cations = sum of anions. For the last 30 yr, many have recommended correcting the anion gap for decreased albumin[10,34] when analyzing metabolic acidosis (examples 1 and 3 in Boxes 1 and 3).

In the presence of hypoalbuminemia, the correction calculation for the anion gap is the same as estimating for the albumin effect on base excess: 0.25 × (42 − albumin, g/l).[10,27,29] A less apparent point is that due to effects on both base excess and the anion gap, hypoalbuminemia can mask acidosis[13] from causes including relative hyperchloremia, increased lactate, and other ions (example 2 in Box 2). For any patient with hypoalbuminemia, the severity of acidifying strong ion and weak acids changes is masked.[12,13]

A decrease in preoperative plasma albumin concentration to 32 g/l will increase base excess and decrease the anion gap by 2.5 mM, and severe hypoalbuminemia (22 g/l) will have a 5-mM change in base excess and anion gap. Ideally plasma albumin should be measured before major surgery and for high-risk patients, and repeated after large volumes of intravenous fluids or blood products (examples 1 and 3 in Boxes 1 and 3). For anesthesiologists, knowing preoperative plasma albumin concentration has added value in assessing patient risk due to the strong association between hypoalbuminemia (less than 35 g/l) and postoperative complications and mortality[35,36] due to both malnutrition and chronic disease.

Unfortunately, point-of-care blood gas machines do not routinely have albumin assays. All approaches to assessing metabolic acidosis status ideally need measured plasma albumin concentration.[2] Without a known plasma albumin concentration, it is possible to still calculate the sodium−chloride and lactate effects on base excess, which provide important information. This also allows calculating other ions but without correcting for albumin effects. In sicker patients, preoperative albumin concentrations are likely to be close to or less than 35 g/l. In two large Australian and New Zealand[35,37] studies, we found the median albumin concentrations for patients undergoing major surgery were 36 g/l for American Society of Anesthesiologists (Schaumburg, Illinois) Physical Status III patients and 32 g/l for American Society of Anesthesiologists Physical Status IV patients. These translate to base excess effects of +1.5 and +2.5 mM, respectively. In the absence of intraoperative albumin therapy, plasma albumin concentrations after major surgery may be lower still, around 30 g/l,[13] a base excess effect of +3 mM. Therefore, in the absence of a known albumin concentration, the other-ion effect on base excess will often be between 1 to 4 mM more negative than calculated if not corrected for changes in albumin (examples 1, 2, and 4 in Boxes 1, 2, and 4). In contrast, therapy with 5% albumin can cause acidosis aggravated by chloride in carrier solutions (example 3 in Box 3).

Intravenous Fluids

The Stewart approach dramatically simplifies understanding intravenous fluid therapy.[21,38] A Stewart explanation for acidosis after saline therapy is that as saline infusion continues, plasma chloride concentration increases faster than sodium concentration, decreasing the sodium−chloride difference, the primary component of the plasma strong ion difference, and is acidifying.[9,39] The key point is the relative difference between the sodium and chloride concentrations.[40] A patient can have hyponatremia but chloride in the reference range, a relative hyperchloremic metabolic acidosis. Infused lactated Ringer's solution (Hartmann's solution)[41] produces less metabolic acidosis than similar volumes of saline[39] because when lactate strong anions are removed from plasma, the plasma strong ion difference is increased, which is alkalinizing.[9] This is a much simpler explanation than complex descriptions of hepatic bicarbonate production.[26,42] Solutions such a PlasmaLyte (Baxter Healthcare, Australia)[41] also have rapidly cleared acetate and gluconate strong anions, again widening the strong ion difference. An alternative explanation for postinfusion acidosis uses bicarbonate dilution as the mechanism[43] but is limited in quantifying effects.

Using Stewart principles, sodium bicarbonate is sodium ions with carbon dioxide.[9] Sodium bicarbonate therapy is alkalinizing because it is an infusion of sodium strong cations without a strong anion. Using the concentrated (1,000 mM, 8.4%) preparations will predominantly increase plasma sodium[44] relative to chloride and increase the strong ion difference, which is alkalizing. Conversely, the more dilute 1.26% (150 mM) solutions available in some countries[45] will require 6.7 times the volume for the same amount of sodium bicarbonate and will largely act

by decreasing plasma chloride concentration rather than increasing sodium,[46] again increasing the strong ion difference (example 3 in Box 3).

Conclusions

Bedside Stewart does not definitively describe metabolic acid–base changes, but is meant to be a useful tool in clinical practice in the operating room and other critical care settings. The main points in using Bedside Stewart in anesthesia care are as follows: (1) the partial pressure of carbon dioxide remains the key respiratory metric; (2) use base excess; (3) consider the sodium−chloride difference; (4) adjust for albumin; (5) measure lactate whenever possible and include in assessing risk; and (6) look for trash (other) ions. Bedside Stewart allows us to quantitatively assess overall metabolic acid–base status and have quantitative insight into the underlying causes for changes. Nileshwar's SALT mnemonic and Friesen's web application[31] can enhance using this approach. I hope that readers will try this bedside approach,[21] and compare it to their current practice for patients requiring arterial or venous blood gas analysis. Give it a test drive.

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Competing Interests

Dr. Story has been appointed an Associate Editor of Anesthesiology, starting January 2021.

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