Stewart's approach to acid base balance in critically ill patients

Essay

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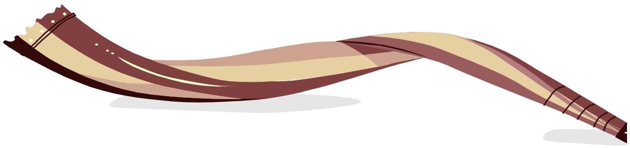

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List of Abbreviations

ABG	Arterial blood gases
AG	Anion gap
$AG_{corrected}$	Corrected anion gap
Alb^-	Albumin
APACHE II	Acute Physiology And Chronic Health Evaluation II
ARDS	Acute respiratory distress syndrome
A_{TOT}	Weak acids
BE_{fw}	Base excess of free water
BE_{Cl}	Base excess of chloride
BE_{XA}	Base excess of unmeasured anions
BE_{alb}	Base excess of albumin
BB	Blood buffer base
BDE	Base-deficit-excess
DPG	Diphosphoglyceric acid
$ECCO_2$ R	Extracorporeal carbon dioxide removal
ECF	extra cellular fluid
ECG	Electrocardiogram
FFP	Fresh frozen plasma
FiO_2	Fraction of Inspired Oxygen
ENaC	Electrogenic epithelial sodium channel
HA	Weak acid
Hb	Hemoglobin
ICU	Intensive Care Unit
ISI	Injury severity index
Ka	Weak acid dissociation constant for HA

List of Abbreviations

mosm	:	milli osmoles
NG	:	nasogastric
NIPPV	:	Noninvasive positive pressure ventilation
NCPAP	:	Nasal continuous positive-pressure ventilation
$PaCO_2$	:	Arterial Partial Carbon Dioxide tension
PaO_2	:	Arterial Partial Oxygen tension
P_eCO_2	:	Partial pressure of carbon dioxide in the expired air
PIM	:	Pediatric Index Mortality
SBE	:	Standardized base excess
SID	:	Strong ion difference
SIG	:	Strong ion gap
SaO_2	:	Oxygen Saturation
SO_4^{-2}	:	Sulphate
UMA	:	Unmeasured anions

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Introduction and aim of the work

Metabolic processes in the body result in the production of relatively large amounts of carbonic, sulfuric, phosphoric, and other acids. A person weighing 70 kg disposes daily of about 13 moles of carbon dioxide through the lungs and about 70 to 100 mmol of titratable, nonvolatile acids, mainly sulfuric and phosphoric acids, through the kidneys. Acid/base balance is generally explained in terms of the carbonic acid-bicarbonate system. This is the most important buffer system and describes the relationship between the respiratory and metabolic components of acid/base balance, the partial pressure of carbon dioxide (PCO_2) and bicarbonate (HCO_3^-), respectively. This relationship is defined by the Henderson and Henderson-Hasselbach equations ***(Pol, 2012***).

The fact that HCO_3^- is not an independent variable and varies with changing PCO_2 has meant that empirically derived correction formulas need to be used to adjust the HCO_3^- for both acute and chronic changes in PCO_2. A parameter termed "standard bicarbonate of blood" was defined as the plasma HCO_3^- in blood that has been equilibrated with a PCO_2 of 40 mmHg at normal body temperature, and used as a reference value to assess the change of HCO_3^- ***(Story & Bellomo, 2004).***

The base excess (BE) was introduced in the late 1950's as a more pure measure of metabolic disturbance. The BE is calculated as the amount of acid or base that must be added to a litre of blood to achieve a normal pH (the hydrogen ion concentration expressed as it's negative log) after correcting the PCO_2 to 40 mmHg at normal body temperature. This was called actual BE (ABE) by Radiometer or in vitro BE by Corning. This definition caused problems in practice, as the pH fall with increasing PCO_2 was greater in the intact individual than for blood in vitro due to hemoglobin’s buffering of CO_2. This led to a fall in BE (a metabolic acidosis) being apparently caused by an acute increase in an individual's PCO_2, which was not the intent of the original definition ***(Wooten, 2003).*** This led to the concept of extracellular Base Excess or in vivo Base Excess (Corning) or Standard Base Excess (SBE, Radiometer) assuming the hemoglobin to be spread throughout the extracellular fluid giving an effective hemoglobin concentration of 6 g/100mL. SBE does not change with acute changes in PCO_2. If, after theoretical equilibration with a PCO_2 of 40 mmHg, the blood sample is acidic compared to normal pH, then alkali must be added to titrate pH back to normal, i.e. it has a negative SBE or a base deficit (BD). On the other hand, if after theoretical equilibration with a PCO_2 of 40 mmHg, the sample has an alkaline pH compared to normal, acid must be added to titrate the pH back to a normal i.e. it has a positive SBE or simply BE ***(Fencl et al., 2000).***

Although these measures may be used to establish if a metabolic abnormality is present or not, they do not give insight into the cause or mechanism underlying the abnormality. The anion gap (AG) has been used to establish, in the case of a metabolic acidosis, whether the acidosis is associated with an increase in unmeasured anion (e.g. lactate) if the AG is raised or, if normal, a hyperchloremic acidosis. However, AG in critically ill patients has been shown to be unreliable, probably because of the generally low albumin levels seen in this patient group ***(Corey, 2003).***

Stewart (1986) proposed an alternative approach to acid/base physiology using physicochemical principles. He analysed the reactions of the components of plasma with respect to dissociation equilibria, electroneutrality and conservation of mass. Stewart developed six equations based upon the dissociation equilibrium reactions of the strong ions, weak ions, CO_2 and the requirement for electroneutrality. Strong ions are those that ionise (dissociate) completely when in solution. Strong ions are spectator ions because their concentrations do not change in solution, as they remain completely dissociated. The dissociation of weak ions on the other hand varies depending upon factors such as changes in pH and temperature within the normal physiological range. Stewart used an older definition of acids and bases in that an acid was a substance that produced an increase in $[H^+]$ as against the more "modern" definition of an acid as a proton (or H^+) donor ***(Rees et al., 2010).***

Although most acid-base abnormalities are easily explained, some remain problematic. Moreover, traditional teaching emphasizes data interpretation rather than pathophysiology. Consequently much confusion exists regarding cause, effect and treatment of acid-base abnormalities .The modern physical chemical approach introduced by Peter Stewart and subsequently refined has enhanced our understanding of these problems, and simplified the clinical application ***(Corey, 2003).***

The AIM OF THIS WORK is to review an updated method (Stewart's approach) for acid base balance in critically ill patients to facilitate its application in different clinical situations.

Origin of Stewart's approach

For the past 100 years acid base chemistry has occupied a special corner of clinical medicine. Physicians generally agree that acid base balance is important, but struggle to understand the science, pathology and application. Undoubtedly, the body carefully controls the relative concentrations of hydrogen and hydroxyl ions in the extracellular and intracellular spaces. Alterations in this balance disrupt transcellular ion pumps leading to significant cardiovascular problems ***(Narins& Emmett,1980)***.

Most acid base abnormalities are easily explained, but some remain problematic. Moreover, traditional teaching emphasizes data interpretation rather than pathophysiology. Consequently much confusion exists regarding cause, effect and treatment of acid base abnormalities. The modern physical-chemical approach, introduced by Peter Stewart and subsequently refined has significantly enhanced our understanding of these problems, and simplified the clinical application ***(Rees et al., 2010).***

In 1981, Stewart, a Canadian physiologist, proposed a radically different approach to acid-base balance. He started by discarding many of the features of the traditional model, including the standard notions of acids and bases. Based upon the laws of mass action, the conservation of mass and the conservation of charge, he derived relatively complex mathematical formulas to describe acid-base balance, while introducing two new variables, the strong ion difference (SID) and the total weak acids (A_{TOT}) ***(Kellum et al., 1995).***

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The traditional approach is often successful in clinical practice. However, the model appears to break down at physiologic extremes. For example, consider a critically ill patient with septic shock and multiple organ failure. The management has consisted of cardiopressors, mechanical ventilation, antibiotics, and large volumes of normal saline solution. Laboratories reveal sodium (Na^+)130 mmol/L, potassium (K^+) 3.0 mmol/L, chloride (Cl^-) 111 mmol/L, albumin 1.5 g/dL, phosphate 2.0 mg/dL, $[HCO_3^-]$ = 9.25 mmol/L, and $PaCO_2$ = 30 mm Hg. The patient is acidotic, with a pH = 7.10. The base excess = -15 meq/L. The anion gap AG = $Na^+ + K^+ - (Cl^- + HCO_3^-)$ is 12.8 meq/L. Although the base excess provides the magnitude of the acid-base disturbance, the traditional model offers no further insight into the mechanism of the acid-base disorder.

These and similar observations prompted Stewart to put forward a novel approach of acid-base balance. By application of Stewart's approach, the patient complains high SIG in the form of unmeasured anions along with normal SIG acidosis due to hyperchloremia ***(Stewart,1981).***

The starting point for Stewart's analysis was the ionic nature of water. Pure water (H_2O) ionises slightly at body temperature to form minute quantities of hydrogen ion (H^+) and hydroxyl ions (OH^-) ***(Corey,2003).***

Physical chemistry of water

The human body is composed principally of water. Water is a simple triatomic molecule with an unequal charge distribution resulting in a H-O-H bond angle of 105^0 as shown in figure 1. This leads to polarity, aggregation, a high surface tension, low vapor pressure, high specific heat capacity, high heat of vaporization and a high boiling point.

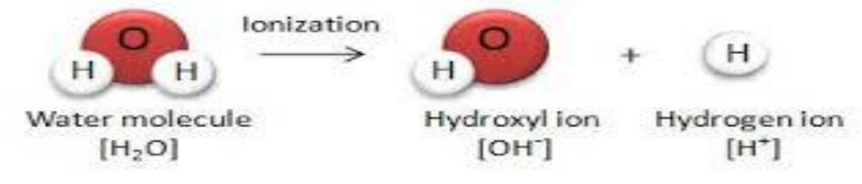

Fig.(1):Dissociation of water molecule***(Emmett & Narins,1977).***

Water is itself slightly ionized into a negatively charged hydroxylated ion and a positively charged protonated ions. Water dissociation is constant and is governed by changes in temperature, dissolved electrolytes and cellular components ***(Narins& Emmett,1980)***.

$$K'w = [H+][OH-]$$

Where K'w is the Autoionization constant for water

In other words, if $[H^+]$ increases, then $[OH^-]$ decreases by the same magnitude. The self ionization of water is miniscule. As a result of the requirement of electroneutrality the $[H^+]$ is the same as the $[OH^-]$. The pH of neutrality is 7.0 at room temperature and 6.8 at 37^0C ***(Marx et al., 1999).***

The important point here is that pure water contains hydrogen ions, albeit in very small quantities, as a result of dissociation and there is a very large potential pool of hydrogen ions in water if conditions result in a change in dissociation. A solution does not become acidic until there are more H^+than OH^-. Water becomes alkaline with falling temperature (at 0^0c, pH is 7.5) and acidic with increasing temperature (at 100^0C, pH is 6.1) ***(Corey, 2003).***

physiologic pH , at which the body resides, differs between the intracellular compartment and between venous and arterial blood. Conventionally, acid base balance refers to changes in hydrogen ion concentration in arterial blood, which reflects extracellular fluid from 7.4. this is reasonable as cells are relatively impervious to ionic materials and changes in fluids, electrolytes and carbon dioxide tension easily