Published in final edited form as:

J Chem Thermodyn. 2012 April 1; 47: 21–27. doi:10.1016/j.jct.2011.09.010.

Buffer standards for the physiological pH of the zwitterionic compound of 3-(*N*-morpholino)propanesulfonic acid (MOPS) from $T = (278.15 \text{ to } 328.15) \text{ K}$

Lakshmi N. Roy, Rabindra N. Roy*, Kathleen A. Allen, Casey J. Mehrhoff, Isaac B. Henson, and Jessica M. Stegner

Hoffman Department of Chemistry, Drury University, 900 N. Benton Ave., Springfield, MO 65802, USA

Abstract

This paper reports the pH values of five NaCl-free buffer solutions and eleven buffer compositions containing NaCl at $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$. Conventional p_{aH} values are reported for sixteen buffer solutions with and without NaCl salt. The operational pH values have been calculated for five buffer solutions and are recommended as pH standards at $T = (298.15 \text{ and } 310.15) \text{ K}$ after correcting the liquid junction potentials. For buffer solutions with the composition $m_1 = 0.04 \text{ mol}\cdot\text{kg}^{-1}$, $m_2 = 0.08 \text{ mol}\cdot\text{kg}^{-1}$, $m_3 = 0.08 \text{ mol}\cdot\text{kg}^{-1}$ at $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$, the pH at 310.15 K is 7.269, which is close to 7.407, the pH of blood serum. It is recommended as a pH standard for biological specimens.

Keywords

Buffers; Ionic Strength; Dissociation Constant; pH

1. Introduction

Biological buffers are of great importance for research in biomedicine and clinical diagnosis. A considerable interest attaches to the acid-base behavior of zwitterionic amino acids [1–2], the buffer solutions of which are useful for the control of acidity in the physiological pH range of 6 to 8. Previously, Roy *et al.* [3–4] have reported the pK_2 values and some limited pH values of buffer solutions of 3-(*N*-morpholino)-propanesulfonic acid (MOPS) at temperatures from $T = (278.15 \text{ to } 328.15) \text{ K}$. In order to provide reliable and accurate pH values, we have studied five MOPS buffer solutions without NaCl and eleven isotonic saline solutions at $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$ in the temperature range (278.15 to 328.15) K. The structure of MOPS is as follows:

The phosphate buffer has been universally used as a physiological pH standard [5], but it may not be ideal for some situations. For example, (i) phosphates can act as inhibitors to enzymatic processes; (ii) phosphate can precipitate with polyvalent cations present in blood

© 2011 Elsevier Ltd. All rights reserved.

*Corresponding author. Tel.: 1 + 417 873 7247; fax: 1 + 417 873 7856, rroy@drury.edu (R. Roy).

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ingredients; and (iii) the temperature coefficient of the pH of the phosphate buffer is -0.0028 K^{-1} as compared to that of whole blood (-0.015 K^{-1}) [6].

Roy *et al.* [7] have reported the pK_2 and pH values of the biological buffer bis-[(2-hydroxyethyl)amino]acetic acid (BICINE). This buffer has been recommended as a pH standard in the range of physiological application. The HEPES buffer was studied by Feng and coworkers [8] and has been certified by the National Institute of Standards and Technology (NIST) as a primary reference pH standard. The values of pK_2 and pH for 3-(*N*-morpholino)-2-hydroxypropanesulfonic acid (MOPSO) [9] have been reported. The pH of these solutions closely matches that of the common clinical media. In 1973, Bates *et al.* [10] recommended pH standard for a buffer solution of $0.06 \text{ mol}\cdot\text{kg}^{-1}$ TRICINE + $0.02 \text{ mol}\cdot\text{kg}^{-1}$ sodiumTRICINEate. Goldberg *et al.* [12] reported the results of the thermodynamic quantities of more than 60 physiological buffers. The review article did not include any reliable results of pH for MOPS.

As shown in figure 1, we now have undertaken to investigate MOPS in order to provide accurate and reproducible pH values for the following buffer compositions: (a) MOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.04 \text{ mol}\cdot\text{kg}^{-1}$; (b) MOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.08 \text{ mol}\cdot\text{kg}^{-1}$; (c) MOPS ($0.03 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.09 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.09 \text{ mol}\cdot\text{kg}^{-1}$; (d) MOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.08 \text{ mol}\cdot\text{kg}^{-1}$; (e) MOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.02 \text{ mol}\cdot\text{kg}^{-1}$; (f) MOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.14 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (g) MOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.12 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (h) MOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.14 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (i) MOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.08 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (j) MOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.04 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.12 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (k) MOPS ($0.05 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.05 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.11 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (l) MOPS ($0.06 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.06 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.10 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (m) MOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.08 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (n) MOPS ($0.06 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.03 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.13 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (o) MOPS ($0.08 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.02 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.14 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$; (p) MOPS ($0.09 \text{ mol}\cdot\text{kg}^{-1}$) + NaMOPS ($0.09 \text{ mol}\cdot\text{kg}^{-1}$) + NaCl ($0.07 \text{ mol}\cdot\text{kg}^{-1}$), $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$.

2. Experimental

MOPS was purchased from Research Organics (Cleveland, OH). The details of the purification by further crystallization as well as the determination of the assay have been reported in an earlier paper [3]. From the titration of purified MOPS with a standard solution of NaOH, the average mass fraction purity was 0.9995 ± 0.001 . All mass measurements were made using MOPS, NaCl (ACS reagent grade dried at $T = 383.15 \text{ K}$), a standard solution of NaOH to prepare NaMOPS, and finally calculated amounts of CO_2 -free doubly distilled water. Apparent mass was converted to mass with buoyancy corrections which, on the average, for all buffer solutions were calculated to be 1.00106 based on the average density of $1.00139 \text{ g}\cdot\text{cm}^{-3}$. The mass uncertainty is estimated to be 0.02 percent.

The preparation of the hydrogen electrodes and the silver-silver chloride electrodes of the thermal electrolytic type [12], the design of the all-glass cells, the purification of the hydrogen gas, preparation of the solutions, control of temperature, and use of digital voltmeter have been reported previously [3–4]. The following cell of the type (A), having no liquid junction, was used:

where m_1 , m_2 and m_3 indicate molalities of the respective species, and 101.325 kPa is the pressure of hydrogen. A correction for the residual liquid-junction potential is needed in order to obtain accurate pH values. The flowing junction cell (B), was used for the evaluation of the liquid junction potential shown with a double vertical line:

For cell (C), the phosphate salts were NIST standard reference materials with the composition KH_2PO_4 ($0.008695 \text{ mol}\cdot\text{kg}^{-1}$) + Na_2HPO_4 ($0.03043 \text{ mol}\cdot\text{kg}^{-1}$) and its solutions are widely used for pH measurements in physiological solutions.

The values of the residual liquid junction potential, $\delta E_j = E_{j(\text{s})} - E_{j(\text{x})}$, for the physiological phosphate solutions and other experimental buffer solutions of MOPS from cell (B) were obtained [4,8] using the following equation:

$$E_{j(\text{s})} = E_s + E_{\text{SCE}}^\circ - k\text{pH(s)} \quad (1)$$

and the similar equation is applicable for $E_{j(\text{x})}$ where pH(s) is replaced by pH(calc) and E_s by $E_{j(\text{x})}$. The value of the standard electrode potential of the saturated calomel electrode, where $E_{\text{SCE}}^\circ = -0.2415 \text{ V}$, $k = 0.059156 \text{ V}$, and $\text{pH(s)} = 7.415$ (physiological phosphate buffer solution) at $T = 298.15 \text{ K}$; $E_{\text{SCE}}^\circ = -0.2335 \text{ V}$, $k = 0.061538 \text{ V}$, and $\text{pH(s)} = 7.395$ at $T = 310.15 \text{ K}$. We have attempted to calculate values of the δE_j for five buffer solutions out of sixteen buffer solutions. The operational definition of pH, indicated as pH(x) ,

$$\text{pH(x)} = \text{pH(s)} + (E_x - E_s + \delta E_j)/k \quad (2)$$

where the subscript (x) refers to the pH of MOPS + NaMOPSate buffer solution; (s) is the reference solution (NIST physiological phosphate buffer) of known pH. The equation (2) takes the following form when $\delta E_j = 0$:

$$\text{pH(x)} = \text{pH(s)} + (E_x - E_s)/k \quad (3)$$

3. Methods and Results

The cell potential data for cell (A) containing five buffer solutions without the presence of the chloride ion and eleven buffer solutions with the addition of NaCl to make $I = 0.16$

mol·kg⁻¹, have been corrected to a hydrogen pressure of 101.325 kPa. The values of the cell potential at $T = 298.15$ K are the average of two readings. The standard deviation, on the average, was 0.02 mV for the experimental temperature range. All these results are listed in tables 1 and 2, respectively.

3.1 The pH of MOPS Buffer

Conventional $p\text{a}_{\text{H}}$ values have been evaluated by the method of Bates *et al.* [10,13–17] for five buffer solutions without NaCl and eleven buffer solutions in the presence of NaCl.

The values of the acidity function $p(a_{\text{H}}\gamma_{\text{Cl}})^{\circ}$ in the absence of Cl^{-} , and $p(a_{\text{H}}\gamma_{\text{Cl}})$ for all eleven buffer solutions in the presence of Cl^{-} were made in the temperature range $T = (278.15 \text{ to } 328.15)$ K. The expression for the acidity function $p(a_{\text{H}}\gamma_{\text{Cl}})$ [10,12] is given by:

$$p(a_{\text{H}}\gamma_{\text{Cl}}) = \frac{E - E^{\circ}}{k} + \log_{10}(m_{\text{Cl}^{-}}/m^{\circ}) \quad (4)$$

where $m^{\circ} = 1 \text{ mol}\cdot\text{kg}^{-1}$, $k = \text{Nernst slope} = RT\ln 10/F$, $R = 8.3145 \text{ J}\cdot\text{mol}^{-1} \text{ K}^{-1}$, $T =$ temperature in kelvins, $F = \text{Faraday constant} = 9.648534 \text{ J}\cdot\text{V}^{-1}\cdot\text{mol}^{-1}$, and $\ln(10) = 2.30259$.

Straight lines of small slopes were obtained when the values of the acidity function $p(a_{\text{H}}\gamma_{\text{Cl}})$ were plotted as a function of $m_{\text{Cl}^{-}}$. The values of the intercepts, $p(a_{\text{H}}\gamma_{\text{Cl}})^{\circ}$, listed in table 3, for five buffer solutions without the presence of NaCl were calculated using equation (5). The acidity function, $p(a_{\text{H}}\gamma_{\text{Cl}})$ for eleven buffers with NaCl are entered in tables 4 and 5 from (278.15 to 328.15) K. The uncertainty introduced in this type of graphical extrapolation is less than 0.002. Conventional $p\text{a}_{\text{H}}$ values were calculated by the following expression:

$$p\text{a}_{\text{H}} = p(a_{\text{H}}\gamma_{\text{Cl}})^{\circ} + \log_{10}\gamma_{\text{Cl}}^{\circ} \quad (5)$$

where the single-ion activity coefficient, $\gamma_{\text{Cl}}^{\circ}$, cannot be measured experimentally. A nonthermodynamic convention [4,5, 16,17] for the estimation of $\gamma_{\text{Cl}}^{\circ}$ has been adopted. The pH values obtained from the residual liquid junction cell are referred to as the “operational” pH, whereas the “conventional” pH calculated from equation (5) is designated as $p\text{a}_{\text{H}}$.

The ‘pH convention’, based on an extended Debye-Hückel equation, has been widely used [5,9]. For the establishment of NIST pH standard [8–9, 13–17], the calculation of $\log_{10}\gamma_{\text{Cl}}^{\circ}$ for all of the buffer-chloride solutions were made by using the following equation:

$$\log_{10}\gamma_{\text{Cl}}^{\circ} = -\frac{A\sqrt{I}}{1+B\alpha^{\circ}\sqrt{I}} + CI \quad (6)$$

where I is the ionic strength of the buffer solution, C is an adjustable parameter, A and B are the Debye-Hückel constants, α° is the ion size parameter, and $B\alpha^{\circ} = 1.38 \text{ kg}^{1/2}\cdot\text{mol}^{-1/2}$ for all experimental temperatures. The following equation is used for the calculation of the parameter C [4,8]:

$$C = C_{298.15} + \alpha\{(T/T^{\circ}) - 298.15\} + \beta\{(T/T^{\circ}) - 298.15\}^2 \quad (7)$$

where $C_{298.15} = 0.032 \text{ kg} \cdot \text{mol}^{-1}$, $\alpha = 6.2 \cdot 10^{-4} \text{ kg} \cdot \text{mol}^{-1}$, $\beta = -8.7 \cdot 10^{-6} \text{ kg} \cdot \text{mol}^{-1}$, $T^\circ = 1 \text{ K}$, and T is the thermodynamic temperature.

The values of pa_H are listed in table 6 for five buffer solutions of MOPS without NaCl and are expressed as a function of temperature.

$$\begin{aligned} &\text{For MOPS (0.02 mol} \cdot \text{kg}^{-1}) \\ &\quad + \text{NaMOPS (0.04 mol} \cdot \text{kg}^{-1}): pa_H \\ &= 7.424 - 1.27 \cdot 10^{-2} \{(T/T^\circ - 298.15)\} \\ &\quad + 2.69 \cdot 10^{-5} \{(T/T^\circ - 298.15)\}^2 \end{aligned} \quad (8)$$

$$\begin{aligned} &\text{For MOPS (0.02 mol} \cdot \text{kg}^{-1}) \\ &\quad + \text{NaMOPS (0.08 mol} \cdot \text{kg}^{-1}): pa_H \\ &= 7.669 - 1.28 \cdot 10^{-2} \{(T/T^\circ - 298.15)\} \\ &\quad + 3.12 \cdot 10^{-5} \{(T/T^\circ - 298.15)\}^2 \end{aligned} \quad (9)$$

$$\begin{aligned} &\text{For MOPS (0.03 mol} \cdot \text{kg}^{-1}) \\ &\quad + \text{NaMOPS (0.09 mol} \cdot \text{kg}^{-1}): pa_H \\ &= 7.587 - 1.29 \cdot 10^{-2} \{(T/T^\circ - 298.15)\} \\ &\quad + 3.33 \cdot 10^{-5} \{(T/T^\circ - 298.15)\}^2 \end{aligned} \quad (10)$$

$$\begin{aligned} &\text{For MOPS (0.04 mol} \cdot \text{kg}^{-1}) \\ &\quad + \text{NaMOPS (0.08 mol} \cdot \text{kg}^{-1}): pa_H \\ &= 7.432 - 1.28 \cdot 10^{-2} \{(T/T^\circ - 298.15)\} \\ &\quad + 1.85 \cdot 10^{-5} \{(T/T^\circ - 298.15)\}^2 \end{aligned} \quad (11)$$

$$\begin{aligned} &\text{For MOPS (0.08 mol} \cdot \text{kg}^{-1}) \\ &\quad + \text{NaMOPS (0.02 mol} \cdot \text{kg}^{-1}): pa_H \\ &= 6.544 - 1.26 \cdot 10^{-2} \{(T/T^\circ - 298.15)\} \\ &\quad + 1.77 \cdot 10^{-5} \{(T/T^\circ - 298.15)\}^2 \end{aligned} \quad (12)$$

where $278.15 \text{ K} \leq T \leq 328.15 \text{ K}$. The standard deviations of regression for the pa_H of the five chloride-free buffer solutions are 0.0014, 0.0015, 0.0012, 0.0015, and 0.0017, respectively.

For eleven buffer solutions containing NaCl at an indicated ionic strength $I = 0.16 \text{ mol} \cdot \text{kg}^{-1}$, the values of pa_H listed in tables 7 and 8 are given by the equations:

For MOPS (0.02 mol · kg⁻¹)+NaMOPS (0.02 mol · kg⁻¹)+NaCl (0.14 mol · kg⁻¹):

$$p a_{\text{H}} = 7.114 - 1.24 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 1.64 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (13)$$

For MOPS (0.02 mol · kg⁻¹)+NaMOPS (0.04 mol · kg⁻¹)+NaCl (0.12 mol · kg⁻¹):

$$p a_{\text{H}} = 7.384 - 1.23 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 2.28 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (14)$$

For MOPS (0.04 mol · kg⁻¹)+NaMOPS (0.02 mol · kg⁻¹)+NaCl (0.14 mol · kg⁻¹):

$$p a_{\text{H}} = 6.820 - 1.30 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 3.21 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (15)$$

For MOPS (0.04 mol · kg⁻¹)+NaMOPS (0.08 mol · kg⁻¹)+NaCl (0.08 mol · kg⁻¹):

$$p a_{\text{H}} = 7.422 - 1.31 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 2.87 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (16)$$

For MOPS (0.04 mol · kg⁻¹)+NaMOPS (0.04 mol · kg⁻¹)+NaCl (0.12 mol · kg⁻¹):

$$p a_{\text{H}} = 7.126 - 1.29 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 2.82 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (17)$$

For MOPS (0.05 mol · kg⁻¹)+NaMOPS (0.05 mol · kg⁻¹)+NaCl (0.11 mol · kg⁻¹):

$$p a_{\text{H}} = 7.130 - 1.31 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 3.65 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (18)$$

For MOPS (0.06 mol · kg⁻¹)+NaMOPS (0.06 mol · kg⁻¹)+NaCl (0.10 mol · kg⁻¹):

$$p a_{\text{H}} = 7.139 - 1.31 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 2.75 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (19)$$

For MOPS (0.08 mol · kg⁻¹)+NaMOPS (0.08 mol · kg⁻¹)+NaCl (0.08 mol · kg⁻¹):

$$p a_{\text{H}} = 7.276 - 1.33 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 4.93 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (20)$$

For MOPS (0.06 mol · kg⁻¹)+NaMOPS (0.03 mol · kg⁻¹)+NaCl (0.13 mol · kg⁻¹):

$$p a_{\text{H}} = 6.828 - 1.30 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 3.38 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (21)$$

For MOPS (0.08 mol · kg⁻¹)+NaMOPS (0.02 mol · kg⁻¹)+NaCl (0.14 mol · kg⁻¹):

$$p a_{\text{H}} = 6.234 - 1.20 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 6.98 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (22)$$

$$\text{For MOPS (0.09 mol} \cdot \text{kg}^{-1}) + \text{NaMOPS (0.03 mol} \cdot \text{kg}^{-1}) + \text{NaCl (0.13 mol} \cdot \text{kg}^{-1}):$$

$$p a_{\text{H}} = 6.795 - 1.32 \cdot 10^{-2} \{(T/T^{\circ} - 298.15)\} + 3.16 \cdot 10^{-5} \{(T/T^{\circ} - 298.15)\}^2 \quad (23)$$

where T is the temperature in K. The standard deviations for regression of the “observed” results from equations (13) to (23) are 0.0016, 0.0015, 0.0020, 0.0013, 0.0012, 0.0015, 0.0020, 0.0013, 0.0018, 0.0015, and 0.0014, respectively.

The potential difference of the cells (B) and (C) at $T = (298.15 \text{ K and } 310.15 \text{ K})$ are given in table 9. By means of the flowing junction cell, the values of δE_j listed in table 10 were calculated by using equation (1). The value of the single-ion activity coefficient, $\log_{10} \gamma_{\text{Cl}}^{\circ}$ cannot be measured experimentally. Covington and Ferra [19] used the Pitzer theory of specific ionic interactions to estimate the single ion activity coefficient at ionic strengths higher than $0.1 \text{ mol} \cdot \text{kg}^{-1}$ in the calculation of the pH standards of the phosphate buffer solutions. In separate publications from this laboratory, we will report pH values of different buffer solutions by using the Pitzer formalism for an ionic strength $I = 0.16 \text{ mol} \cdot \text{kg}^{-1}$ at $T = (298.15 \text{ K and } 310.15 \text{ K})$. From table 11, the calculated pH values and the values obtained from the δE_j corrections are in very good agreement (within ± 0.001). For example, a comparison of the values of pH between calculated and inclusion of the residual junction potential is 7.241 and 7.240, respectively, for $m_1 = 0.02 \text{ mol} \cdot \text{kg}^{-1}$ and $m_2 = 0.04 \text{ mol} \cdot \text{kg}^{-1}$, and $m_3 = 0.012 \text{ mol} \cdot \text{kg}^{-1}$ at 310.15 K. The total uncertainties were estimated by combining the various sources of error: (i) assumption for the calculation of the $\log_{10} \gamma_{\text{Cl}}^{\circ}$; (ii) extrapolation to $p(a_{\text{HCl}})^{\circ}$ at $m_{\text{Cl}^-} = 0$; and (iii) residual liquid junction potential measurement. Thus, the overall uncertainty is about $\pm 0.009 \text{ pH unit}$. The operational pH values at $T = (298.15 \text{ K and } 310.15 \text{ K})$ (table 11) for five buffer solutions having the compositions (with and without the presence of NaCl) are recommended as secondary pH standards for the measurement of the pH of physiological fluids.

Acknowledgments

The authors are grateful for the funding from the National Institutes of Health (AREA), under the grant 2-R15 GM 066866-03 and the diversity supplemental grant 3-R15 GM 066866-03 S1. The authors would also like to thank Taichi Fukubayashi and Joshua Guindon for their dedication and hard work. The content of this paper is the sole responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the National Institutes of General Medical Sciences.

References

1. Good NE, Winget GD, Winter W, Connolly TN, Izawa S, Singh RMM. *Biochemistry*. 1966; 5:467–477. [PubMed: 5942950]
2. Ferguson WJ, Braunschweiler KI, Braunschweiler WR, Smith JR, McCormick JJ, Wasmann CC, Jarvis NP, Bell DH, Good NE. *Biochemistry*. 1980; 19:300–310.
3. Roy RN, Carlsten JL, Niederschmidt J, Good WS, Rook JM, Brew C, Kilker AJ, Roy LN, Kuhler KM. *J Solution Chem*. 1997; 26:309–317.
4. Roy RN, Mrad DR, Lord PA, Carlsten JA, Good WS, Allsup P, Roy LN, Kuhler KM, Koch WF, Wu YC. *J Solution Chem*. 1998; 27:73–87.
5. Bower VE, Paabo M, Bates RG. *J Res Natl Bur Stand*. 1961; 65A:267–270.
6. Durst RA, Staples BR. *Clin Chem*. 1972; 18:206–208. [PubMed: 5020814]
7. Roy LN, Roy RN, Denton CE, LeNoue SR, Roy CN, Ashkenazi S, Williams TB, Church DR, Fuge MS, Sreepada KS. *J of Solution Chem*. 2006; 35:305–324.
8. Feng D, Koch WF, Wu YC. *Anal Chem*. 1989; 61:1400–1405.
9. Wu YC, Berezensky PA, Feng D, Koch WF. *Anal Chem*. 1993; 65:1084–1087.

10. Bates RG, Roy RN, Robinson RA. *Anal Chem.* 1973; 45:1663–1666. [PubMed: 4756738]
11. Goldberg RN, Kishore N, Lennen RM. *J Phys Chem Ref Data.* 2002; 31:231–370.
12. Bates, RG. *Determination of pH, Theory and Practice.* 2. Vol. Chapter 10. Wiley; 1973. p. 330
13. Bates RG. *J Res Natl Bur Stand.* 1962; 66A:179–184.
14. Bates RG, Guggenheim EA. *Pure Appl Chem.* 1960; 1:163–168.
15. Bates RG, Vega CA, White DR Jr. *Anal Chem.* 1978; 50:1295–1300.
16. Buck RP, Rondinini S, Covington AK, Baucke FGK, Brett CMA, Camoes MF, Milton MJT, Mussini T, Naumann R, Pratt KW, Spitzer P, Wilson GS. *Pure Appl Chem.* 2002; 74:2169–2200.
17. Camoes MF, Lito MJG, Ferra MIA, Covington AK. *Pure Appl Chem.* 1997; 69:1325–1333.
18. Wu YC, Feng D, Koch WF. *J Solution Chem.* 1989; 18:641–649.
19. Covington AK, Ferra MIA. *J Solution Chem.* 1994; 23:1–10.

Highlights

- i.** This work reports pH values of MOPS buffer
- ii.** Liquid junction potential correct is applied
- iii.** These values will be used by clinical and biomedical scientists
- iv.** The pH values lie within 6.8 to 7.5

FIGURE 1.
3-(*N*-morpholino)-propanesulfonic acid (MOPS)

TABLE 1

Electromotive force E of Cell A (V): $\text{Pt(s)}; \text{H}_2(\text{g}, p = 101.325 \text{ kPa}) | \text{MOPS} (m_1), \text{NaMOPS} (m_2), \text{NaCl} (m_3) | \text{AgCl(s)}, \text{Ag(s)}$

$m/\text{mol}\cdot\text{kg}^{-1}$		T/K														
m_1	m_2	m_3	278.15	283.15	288.15	293.15	298.15	303.15	308.15	310.15	313.15	318.15	323.15	328.15	333.15	338.15
0.02	0.04	0.005	0.78930	0.79272	0.79604	0.79908	0.80184	0.80455	0.80701	0.80805	0.80940	0.81155	0.81341	0.81545		
0.02	0.04	0.010	0.77215	0.77526	0.77820	0.78091	0.78345	0.78583	0.78805	0.78889	0.79006	0.79191	0.79360	0.79520		
0.02	0.04	0.015	0.76200	0.76495	0.76769	0.77020	0.77262	0.77480	0.77689	0.77761	0.77870	0.78036	0.78192	0.78330		
0.02	0.04	0.020	0.75451	0.75734	0.75988	0.76225	0.76459	0.76662	0.76865	0.76924	0.77025	0.77179	0.77335	0.77447		
0.02	0.08	0.005	0.80530	0.80898	0.81257	0.81587	0.81880	0.82182	0.82458	0.82569	0.82713	0.82969	0.83189	0.83421		
0.02	0.08	0.010	0.78935	0.79279	0.79602	0.79904	0.80176	0.80454	0.80701	0.80798	0.80932	0.81145	0.81342	0.81533		
0.02	0.08	0.015	0.78013	0.78341	0.78645	0.78931	0.79196	0.79446	0.79692	0.79783	0.79909	0.80108	0.80296	0.80467		
0.02	0.08	0.020	0.77387	0.77705	0.77997	0.78270	0.78526	0.78766	0.78994	0.79078	0.79199	0.79371	0.79555	0.79704		
0.03	0.09	0.005	0.80076	0.80435	0.80771	0.81092	0.81379	0.81662	0.81937	0.82044	0.82182	0.82427	0.82645	0.82852		
0.03	0.09	0.010	0.78439	0.78772	0.79080	0.79371	0.79628	0.79881	0.80119	0.80214	0.80338	0.80545	0.80734	0.80908		
0.03	0.09	0.015	0.77473	0.77787	0.78080	0.78352	0.78596	0.78830	0.79044	0.79132	0.79249	0.79437	0.79611	0.79766		
0.03	0.09	0.020	0.76812	0.77115	0.77397	0.77656	0.77890	0.78106	0.78304	0.78393	0.78499	0.78661	0.78823	0.78964		
0.04	0.08	0.005	0.79131	0.79479	0.79820	0.80112	0.80404	0.80672	0.80923	0.81012	0.81143	0.81338	0.81540	0.81719		
0.04	0.08	0.010	0.77465	0.77788	0.78088	0.78358	0.78604	0.78838	0.79087	0.79136	0.79252	0.79426	0.79594	0.79742		
0.04	0.08	0.015	0.76484	0.76788	0.77062	0.77323	0.77535	0.77746	0.77992	0.78021	0.78126	0.78288	0.78440	0.78572		
0.04	0.08	0.020	0.75780	0.76085	0.76345	0.76595	0.76780	0.76975	0.77220	0.77228	0.77330	0.77485	0.77623	0.77745		
0.08	0.02	0.005	0.73957	0.74232	0.74450	0.74684	0.74880	0.75065	0.75226	0.75289	0.75369	0.75477	0.75583	0.75655		
0.08	0.02	0.010	0.72287	0.72528	0.72718	0.72914	0.73087	0.73239	0.73369	0.73417	0.73478	0.73563	0.73636	0.73673		
0.08	0.02	0.015	0.71280	0.71499	0.71674	0.71846	0.72006	0.72135	0.72247	0.72283	0.72334	0.72407	0.72460	0.72477		
0.08	0.02	0.020	0.70572	0.70778	0.70941	0.71097	0.71246	0.71361	0.71459	0.71485	0.71530	0.71595	0.71634	0.71635		
E° (V) of Ag-AgCl:			0.23416	0.23147	0.22863	0.22562	0.22244	0.21913	0.21572	0.21429	0.21214	0.20840	0.20455	0.20064		

TABLE 2
Electromotive force E of Cell A (V): Pt(s); H₂(g, $p = 101.325$ kPa) | MOPS (m_1), NaMOPS (m_2), NaCl (m_3) | AgCl(s), Ag(s)

$m/\text{mol}\cdot\text{kg}^{-1}$				T/K															
m_1	m_2	m_3		278.15	283.15	288.15	293.15	298.15	303.15	308.15	310.15	313.15	318.15	323.15	328.15				
0.02	0.02	0.14	0.69493	0.69692	0.69843	0.69979	0.70125	0.70225	0.70325	0.70350	0.70390	0.70427	0.70448	0.70455					
0.02	0.04	0.12	0.71356	0.71568	0.71787	0.71938	0.72120	0.72273	0.72402	0.72442	0.72512	0.72599	0.72665	0.72730					
0.04	0.02	0.14	0.67956	0.68097	0.68220	0.68324	0.68391	0.68450	0.68472	0.68513	0.68538	0.68552	0.68553	0.68541					
0.04	0.08	0.08	0.72626	0.72845	0.73055	0.73230	0.73397	0.73521	0.73653	0.73696	0.73761	0.73858	0.73932	0.74005					
0.04	0.04	0.12	0.70007	0.70169	0.70334	0.70474	0.70602	0.70700	0.70776	0.70807	0.70846	0.70899	0.70942	0.70960					
0.05	0.05	0.11	0.70279	0.70439	0.70584	0.70728	0.70859	0.70945	0.71022	0.71052	0.71097	0.71162	0.71208	0.71241					
0.06	0.06	0.10	0.70527	0.70716	0.70891	0.71011	0.71169	0.71240	0.71326	0.71358	0.71397	0.71452	0.71503	0.71525					
0.08	0.08	0.08	0.71208	0.71354	0.71523	0.71660	0.71785	0.71883	0.71991	0.72018	0.72066	0.72139	0.72218	0.72278					
0.06	0.03	0.13	0.68187	0.68325	0.68452	0.68549	0.68629	0.68692	0.68714	0.68760	0.69782	0.68799	0.68809	0.68801					
0.08	0.02	0.14	0.64691	0.64764	0.64806	0.64855	0.64909	0.64957	0.64979	0.65008	0.65029	0.65045	0.65073	0.65132					
0.09	0.03	0.13	0.67325	0.67449	0.67554	0.67645	0.67677	0.67715	0.67737	0.67747	0.67753	0.67738	0.67721	0.67684					

TABLE 3

$p(a_H\gamma_{Cl})^\circ$ of (MOPS+ NaMOPS) buffer solutions from (278.15 to 328.15) K, computed using equation (5)

T/K	$0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS}$ $I = 0.04 \text{ mol}\cdot\text{kg}^{-1}$	$0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.08 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS}$ $I = 0.08 \text{ mol}\cdot\text{kg}^{-1}$	$0.03 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.09 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS}$ $I = 0.09 \text{ mol}\cdot\text{kg}^{-1}$	$0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.08 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS}$ $I = 0.08 \text{ mol}\cdot\text{kg}^{-1}$	$0.08 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS}$ $I = 0.02 \text{ mol}\cdot\text{kg}^{-1}$
278.15	7.768	8.038	7.962	7.797	6.863
283.15	7.698	7.968	7.892	7.727	6.798
288.15	7.633	7.902	7.824	7.663	6.728
293.15	7.568	7.837	7.758	7.594	6.667
298.15	7.502	7.769	7.691	7.534	6.603
303.15	7.441	7.709	7.629	7.472	6.542
308.15	7.378	7.646	7.569	7.408	6.481
310.15	7.357	7.624	7.546	7.386	6.459
313.15	7.321	7.586	7.508	7.349	6.422
318.15	7.263	7.531	7.453	7.286	6.361
323.15	7.203	7.472	7.396	7.229	6.303
328.15	7.151	7.412	7.341	7.171	6.244

TABLE 4

$p(a_{H^+})$ of (MOPS + NaMOPS) buffer solutions from (278.15 to 328.15) K, computed using equation (4)

T/K	0.02 mol·kg ⁻¹ MOPS + 0.02 mol·kg ⁻¹ NaMOPS + 0.14 mol·kg ⁻¹ NaCl		0.02 mol·kg ⁻¹ MOPS + 0.04 mol·kg ⁻¹ NaMOPS + 0.12 mol·kg ⁻¹ NaCl		0.04 mol·kg ⁻¹ MOPS + 0.02 mol·kg ⁻¹ NaMOPS + 0.14 mol·kg ⁻¹ NaCl		0.04 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS + 0.08 mol·kg ⁻¹ NaCl		0.04 mol·kg ⁻¹ MOPS + 0.04 mol·kg ⁻¹ NaMOPS + 0.12 mol·kg ⁻¹ NaCl	
	$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹	
278.18	7.495		7.766		7.217		7.820		7.521	
283.15	7.431		7.698		7.147		7.749		7.449	
288.15	7.363		7.636		7.079		7.682		7.382	
293.15	7.298		7.568		7.014		7.614		7.316	
298.15	7.240		7.510		6.947		7.550		7.254	
303.15	7.178		7.452		6.883		7.483		7.190	
308.15	7.120		7.393		6.817		7.421		7.127	
310.15	7.096		7.369		6.797		7.396		7.103	
313.15	7.061		7.335		6.763		7.360		7.067	
318.15	7.001		7.279		6.704		7.302		7.009	
323.15	6.943		7.222		6.648		7.243		6.953	
328.15	6.886		7.168		6.592		7.188		6.896	

TABLE 5

$p(a_{H^+})$ of (MOPS + NaMOPS) buffer solutions from (278.15 to 328.15) K, computed using equation (4)

T/K	0.05 mol·kg ⁻¹ MOPS + 0.05 mol·kg ⁻¹ NaMOPS + 0.11 mol·kg ⁻¹ NaCl		0.06 mol·kg ⁻¹ MOPS + 0.06 mol·kg ⁻¹ NaMOPS + 0.10 mol·kg ⁻¹ NaCl		0.08 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS + 0.08 mol·kg ⁻¹ NaCl		0.06 mol·kg ⁻¹ MOPS + 0.03 mol·kg ⁻¹ NaMOPS + 0.13 mol·kg ⁻¹ NaCl		0.08 mol·kg ⁻¹ MOPS + 0.02 mol·kg ⁻¹ NaMOPS + 0.14 mol·kg ⁻¹ NaCl		0.09 mol·kg ⁻¹ MOPS + 0.03 mol·kg ⁻¹ NaMOPS + 0.13 mol·kg ⁻¹ NaCl	
	$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹	
278.15	7.533		7.536		7.563		7.226		6.625		7.070	
283.15	7.459		7.467		7.484		7.155		6.554		6.999	
288.15	7.388		7.401		7.414		7.088		6.482		6.930	
293.15	7.322		7.330		7.344		7.020		6.417		6.865	
298.15	7.259		7.270		7.278		6.955		6.358		6.794	
303.15	7.193		7.201		7.211		6.891		6.302		6.729	
308.15	7.129		7.137		7.149		6.824		6.246		6.665	
310.15	7.105		7.113		7.124		6.805		6.228		6.641	
313.15	7.070		7.077		7.087		6.770		6.198		6.604	
318.15	7.013		7.018		7.030		6.711		6.149		6.543	
323.15	6.957		6.962		6.976		6.655		6.105		6.486	
328.15	6.902		6.904		6.923		6.599		6.068		6.428	

TABLE 6

pH of (MOPS + NaMOPS) buffer solutions from (278.15 to 328.15) K, computed using equations (4) – (7)

T/K	0.02 mol·kg ⁻¹ MOPS + 0.04 mol·kg ⁻¹ NaMOPS <i>I</i> = 0.04 mol·kg ⁻¹	0.02 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS <i>I</i> = 0.08 mol·kg ⁻¹	0.03 mol·kg ⁻¹ MOPS + 0.09 mol·kg ⁻¹ NaMOPS <i>I</i> = 0.09 mol·kg ⁻¹	0.04 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS <i>I</i> = 0.08 mol·kg ⁻¹	0.08 mol·kg ⁻¹ MOPS + 0.02 mol·kg ⁻¹ NaMOPS <i>I</i> = 0.02 mol·kg ⁻¹
278.15	7.690	7.938	7.858	7.697	6.804
283.15	7.621	7.868	7.788	7.627	6.739
288.15	7.556	7.802	7.719	7.563	6.669
293.15	7.491	7.737	7.654	7.494	6.608
298.15	7.424	7.667	7.586	7.433	6.543
303.15	7.362	7.607	7.523	7.371	6.482
308.15	7.298	7.544	7.463	7.306	6.420
310.15	7.277	7.521	7.439	7.283	6.398
313.15	7.240	7.483	7.401	7.245	6.361
318.15	7.182	7.427	7.345	7.182	6.299
323.15	7.121	7.367	7.287	7.124	6.241
328.15	7.068	7.314	7.231	7.066	6.181

TABLE 7

pH of (MOPS + NaMOPS) buffer solutions from (278.15 to 328.15) K computed using equations (4) – (6)

T/K	$0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS} + 0.14 \text{ mol}\cdot\text{kg}^{-1} \text{ NaCl}$ $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$	$0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS} + 0.12 \text{ mol}\cdot\text{kg}^{-1} \text{ NaCl}$ $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$	$0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.02 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS} + 0.14 \text{ mol}\cdot\text{kg}^{-1} \text{ NaCl}$ $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$	$0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.08 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS} + 0.08 \text{ mol}\cdot\text{kg}^{-1} \text{ NaCl}$ $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$	$0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ MOPS} + 0.04 \text{ mol}\cdot\text{kg}^{-1} \text{ NaMOPS} + 0.12 \text{ mol}\cdot\text{kg}^{-1} \text{ NaCl}$ $I = 0.16 \text{ mol}\cdot\text{kg}^{-1}$
278.15	7.370	7.640	7.091	7.694	7.396
283.15	7.305	7.572	7.021	7.624	7.323
288.15	7.238	7.511	6.954	7.556	7.257
293.15	7.173	7.443	6.889	7.489	7.191
298.15	7.114	7.384	6.820	7.424	7.127
303.15	7.051	7.325	6.756	7.356	7.063
308.15	6.992	7.265	6.689	7.293	6.999
310.15	6.968	7.241	6.669	7.269	6.975
313.15	6.932	7.207	6.634	7.232	6.939
318.15	6.872	7.149	6.575	7.173	6.880
323.15	6.831	7.092	6.517	7.113	6.823
328.15	6.754	7.037	6.460	7.056	6.765

TABLE 8

pH of (MOPS + NaMOPS) buffer solutions from (278.15 to 328.15) K, computed using equations (4) – (6)

T/K	0.05 mol·kg ⁻¹ MOPS + 0.05 mol·kg ⁻¹ NaMOPS + 0.11 mol·kg ⁻¹ NaCl		0.06 mol·kg ⁻¹ MOPS + 0.06 mol·kg ⁻¹ NaMOPS + 0.10 mol·kg ⁻¹ NaCl		0.08 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS + 0.08 mol·kg ⁻¹ NaCl		0.06 mol·kg ⁻¹ MOPS + 0.03 mol·kg ⁻¹ NaMOPS + 0.13 mol·kg ⁻¹ NaCl		0.08 mol·kg ⁻¹ MOPS + 0.02 mol·kg ⁻¹ NaMOPS + 0.14 mol·kg ⁻¹ NaCl		0.09 mol·kg ⁻¹ MOPS + 0.03 mol·kg ⁻¹ NaMOPS + 0.13 mol·kg ⁻¹ NaCl	
	$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹		$I = 0.16$ mol·kg ⁻¹	
278.15	7.407	7.411	7.563	7.101	6.499	7.070						
283.15	7.334	7.342	7.484	7.030	6.428	7.000						
288.15	7.263	7.275	7.414	6.962	6.357	6.931						
293.15	7.197	7.205	7.344	6.895	6.292	6.865						
298.15	7.133	7.144	7.278	6.828	6.232	6.794						
303.15	7.066	7.074	7.211	6.764	6.175	6.729						
308.15	7.001	7.010	7.149	6.697	6.118	6.665						
310.15	6.977	6.986	7.124	6.677	6.100	6.641						
313.15	6.941	6.948	7.087	6.069	6.641	6.604						
318.15	6.884	6.888	7.030	6.582	6.019	6.543						
323.15	6.827	6.831	6.976	6.525	5.975	6.486						
328.15	6.770	6.772	6.923	6.468	5.937	6.428						

TABLE 9

Emf of Cell B for MOPS buffer

$m_1 \text{ mol}\cdot\text{kg}^{-1}$	$m_2 \text{ mol}\cdot\text{kg}^{-1}$	$m_3 \text{ mol}\cdot\text{kg}^{-1}$	$T = 298.15 \text{ K} \quad T = 310.15 \text{ K}$	
			E/V	
0.03	0.09	0.00	0.69239	0.69350
0.02	0.04	0.12	0.67867	0.67965
0.04	0.08	0.08	0.68115	0.68154
0.06	0.06	0.10	0.66458	0.66407
0.08	0.08	0.08	0.67251	0.67256
Emf of Cell C ^a				
Cell C				
			$T = 298.15 \text{ K} \quad T = 310.15 \text{ K}$	
0.008695 mol·kg ⁻¹ KH ₂ PO ₄ + 0.0304 mol·kg ⁻¹ Na ₂ HPO ₄			0.68275	0.69147

^a Published data [8,9] for physiological phosphate buffer solutions

TABLE 10

Values of the liquid junction potentials for MOPS buffer at (298.15 and 310.15) K

System <i>m</i> /mol·kg ⁻¹	δE_j^a /mV	
	<i>T</i> = 298.15 K	<i>T</i> = 310.15 K
Physiological phosphate (0.008695 <i>m</i> KH ₂ PO ₄ + 0.03043 <i>m</i> NaCl)	2.6	2.9
0.03 mol·kg ⁻¹ MOPS + 0.09 mol·kg ⁻¹ NaMOPS + 0.00 mol·kg ⁻¹ NaCl	0.5	0.7
0.02 mol·kg ⁻¹ MOPS + 0.04 mol·kg ⁻¹ NaMOPS + 0.12 mol·kg ⁻¹ NaCl	2.2	2.3
0.04 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS + 0.08 mol·kg ⁻¹ NaCl	2.1	2.2
0.06 mol·kg ⁻¹ MOPS + 0.06 mol·kg ⁻¹ NaMOPS + 0.10 mol·kg ⁻¹ NaCl	2.1	2.2
0.08 mol·kg ⁻¹ MOPS + 0.08 mol·kg ⁻¹ NaMOPS + 0.08 mol·kg ⁻¹ NaCl	2.1	2.2

^aObtained from equation (1) using Emf from table 9, *k* = Nernst slope with values 0.059156 at *T* = 298.15 K, and 0.061538 at *T* = 310.15 K; the pH of the primary reference phosphate buffer is 7.415 and 7.395 at (298.15 and 310.15) K, respectively; E_{SCE}° = electrode potential of the saturated calomel electrode = -0.2415 and -0.2335 at (298.15 and 310.15) K, respectively.

TABLE 11

Values of pH at (298.15 and 310.15) K for MOPS buffer solutions

Cell B $m/\text{mol}\cdot\text{kg}^{-1}$		Ionic Strength, I	$T = 298.15 \text{ K}$			$T = 310.15 \text{ K}$		
m_1	m_2	m_3	Without ^a δE_j corr	With ^b δE_j corr	Calc ^c	Without ^a δE_j corr	With ^b δE_j corr	Calc ^c
0.03	0.09	0.00	7.578	7.586	7.586	7.428	7.439	7.439
0.02	0.04	0.12	7.346	7.383	7.384	7.203	7.240	7.241
0.04	0.08	0.08	7.388	7.423	7.424	7.235	7.269	7.269
0.06	0.06	0.10	7.109	7.143	7.144	6.950	6.985	6.986
0.08	0.08	0.08	7.242	7.277	7.278	7.088	7.123	7.124

^aValues obtained from equation (3) and data of table 9

^bObtained from equation (2) and δE_j data of table 10

^cObtained from tables 6, 7, and 8