JOURNAL OF CHEMICAL & ENGINEERING DATA

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Complex Equilibria in Aqueous Solutions of Chromium(III) with Some Biological pH Buffers

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ABSTRACT: In this study, we examined the complex formation of the Cr(III) ion with a variety of biological pH buffers [tris(hydroxymethyl)aminomethane (TRIS), *N*-[tris(hydroxymethyl)methyl]-2-aminoethanesulfonic acid (TES), *N*-[tris(hydroxymethyl)methyl]-3-aminopropanesulfonic acid (TAPS), *N*-[tris(hydroxymethyl)methyl]-3-amino-2-hydroxypropanesulfonic acid (TAPSO), *N*-tris(hydroxymethyl)methyl-4-aminobutane sulfonic acid (TABS), 4-morpholine ethane sulfonic acid (MES), 4-morpholine propane sulfonic acid (MOPS), 3-morpholino-2-hydroxypropane sulfonic acid (MOPSO), and 4-(*N*-morpholino)butanesulfonic acid (MOBS)] by potentiometric measurements at 310.15 K and ionic strength I = 0.16 mol·dm^{-3} KCl. The protonation constants of the biological buffers were determined and discussed, under the above conditions. The overall stability constants were obtained by the least-squares curve-fitting program HYPERQUAD 2008. As a result of the numerical treatment, a model composed of five main species CrL, CrL_2, $CrL_2(OH)$, $CrL_2(OH)_2$, and CrL_3 was obtained, where L = TRIS, TAPS, TAPSO, TABS, and MOBS. The first four complexes have also found from the systems containing MES, MOPS, or MOPSO. The stabilities of the binary complexes appear to follow the order TABS > TAPSO > TRIS > TAPS > TES and MOBS > MOPS > MOPSO > MES for the TRIS family and morpholine family, respectively. The trend in stability constants of the binary complexes was discussed. The species distribution diagrams of Cr−(buffer)$_x$−(OH)$_y$ systems were evaluated as a function of pH. In addition, the influence of CH_2 (between the zwitterions) and OH (nearby the sulfonic group) on the stability constants was studied. The results show that the insertion of methylene groups between the amino group and the sulfonic group enhanced the complexation. While the (OH) group of TAPSO may be taking part in coordination with the Cr(III) ion, it is not for MOPSO.

INTRODUCTION

Nearly a half-century ago, Good et al.[1] published an excellent paper in which they invented 12 biological buffers to supplement or replace tris(hydroxymethyl)aminomethane (TRIS), borate, glycylglycine, imidazole, 5,5-diethylbarbiturate (Veronal), maleate, and dimethylglutarate buffers commonly used by biologists and biochemists. Ten are zwitterionic amino acids, either *N*-substituted taurines or *N*-substituded glycines, and two are cationic primary aliphatic amines (cholamine and glycineamide). Since the first report by Good and his colleagues, several biological buffers have been developed.[2−4] All Good's buffers (plus TRIS) have now become the predominant buffer systems used in the study of pH-dependent phenomena for biological and physiological studies.[5]

In designing Good's buffers, among several criteria, the prevention of metal complexation was one of the criteria to select a buffer for use in vitro biological systems.[1,2] Nowadays, some buffers are normally used routinely in speciation studies because of their purported weak-to nonexistent complexation properties.[6] The metal complexation of buffer should be taken into consideration. Clearly, there are conflicting data in the literature on studying identical metal−cation protein systems, at the same pH in carefully performed experiments. One possible explanation for these conflicting data is that pH buffers tend to bind metal ions, especially because the pH buffers are usually present in significant excess. In fact, numerous studies showing the interactions between metal ions and most of Good's buffers have appeared in the literature.[7−16] A review written by Magyar and Godwina[17] emphasizes the pitfalls of binding metal cations with noninnocent pH buffers. We observe that no report is concerned about the suitability of these pH buffers and the chromium(III) ion. In this context, we believe that the study of the interactions of some important biological buffers with chromium(III) may have implications on biochemical, biological, or environmental studies.

Chromium(III) was selected for the present study due to its biological functions. Chromium(III) is required for carbohydrate and lipid metabolism in mammals.[18] It has been proposed that the chromium serves as a critical cofactor in the action of insulin.[18]

In the present work, the overall stability constants of complexes of some biological buffers with Cr(III) in aqueous solution at 310.15 K and I = 0.16 mol·dm^{-3} KCl were determined by potentiometric titration using a HYPERQUAD 2008 computational program. These pH buffers have been used in various types of chemistry studies.[5] Moreover, these buffers are structurally related, representing two families of buffers (TRIS family and morpholine family). The TRIS family members are TRIS, *N*-[tris(hydroxymethyl)methyl]-2-aminoethanesulfonic acid (TES), *N*-[tris(hydroxymethyl)methyl]-3-aminopropanesulfonic acid (TAPS), *N*-[tris(hydroxymethyl)methyl]-3-amino-2-hydroxypropanesulfonic acid (TAPSO), and *N*-tris(hydroxymethyl)-methyl-4-aminobutane sulfonic acid (TABS) buffers. While,

Received: April 8, 2011
Accepted: July 19, 2011
Published: August 05, 2011

Table 1. Experimental Conditions Used to Determine the Overall Stability Constants of the Systems under Investigation at 310.15 K and I = 0.16 mol·dm^{-3} KCl

	T_L				T_{cr}	
system	mol·dm^{-3}	pH range	system T_L:T_{cr}	T_L:T_{cr}	mol·dm^{-3}	pH range
TRIS family			TRIS family			
proton-TRIS	$1\cdot10^{-3}$	2.70−10.51	Cr(III)-TRIS	1:1	$1\cdot10^{-3}$	2.64−6.25
proton-TES	$1\cdot10^{-3}$	2.55−7.65		2:1	$5\cdot10^{-4}$	2.67−7.39
proton-TAPS	$1\cdot10^{-3}$	2.51−10.13		3:1	$3\cdot10^{-4}$	2.68−7.45
proton-TAPSO	$1\cdot10^{-3}$	2.63−9.80	Cr(III)-TES	1:1	$1\cdot10^{-3}$	2.45−6.15
proton-TABS	$1\cdot10^{-3}$	2.47−10.51		2:1	$5\cdot10^{-4}$	2.47−6.65
				3:1	$3\cdot10^{-4}$	2.52−6.37
morpholine family			Cr(III)-TAPS	1:1	$1\cdot10^{-3}$	2.44−5.57
proton-MES	$1\cdot10^{-3}$	2.47−6.54		2:1	$5\cdot10^{-4}$	2.51−6.73
proton-MOPS	$1\cdot10^{-3}$	2.46−7.53		3:1	$3\cdot10^{-4}$	2.47−7.36
proton-MOPSO	$1\cdot10^{-3}$	2.52−6.59	Cr(III)-TAPSO	1:1	$1\cdot10^{-3}$	2.57−5.69
proton-MOBS	$1\cdot10^{-3}$	2.46−7.78		2:1	$5\cdot10^{-4}$	2.49−6.73
				3:1	$3\cdot10^{-4}$	2.49−6.30
			Cr(III)-TABS	1:1	$1\cdot10^{-3}$	2.44−5.41
				2:1	$5\cdot10^{-4}$	2.41−7.57
				3:1	$3\cdot10^{-4}$	2.51−7.12
			morpholine family			
			Cr(III)-MES	1:1	$1\cdot10^{-3}$	2.51−5.39
				2:1	$5\cdot10^{-4}$	2.47−5.99
				3:1	$3\cdot10^{-4}$	2.47−6.16
			Cr(III)-MOPS	1:1	$1\cdot10^{-3}$	2.47−5.54
				2:1	$5\cdot10^{-4}$	2.46−6.82
				3:1	$3\cdot10^{-4}$	2.46−6.61
			Cr(III)-MOPSO	1:1	$1\cdot10^{-3}$	2.49−5.66
				2:1	$5\cdot10^{-4}$	2.49−6.36
				3:1	$3\cdot10^{-4}$	2.52−6.57
			Cr(III)-MOBS	1:1	$1\cdot10^{-3}$	2.52−5.64
				2:1	$5\cdot10^{-4}$	2.43−6.91
				3:1	$3\cdot10^{-4}$	2.45−6.39

the morpholine family members are 4-morpholine ethane sulfonic acid (MES), 4-morpholine propane sulfonic acid (MOPS), 3-morpholino-2-hydroxypropane sulfonic acid (MOPSO), and 4-(*N*-morpholino)butanesulfonic acid (MOBS) buffers. The TRIS family and morpholine family are, respectively, derived from TRIS and morpholine molecules. It is seen that there are two sets of buffers that differ in the length of the alkane group side chains: the *N*-tris(hydroxymethyl)methyl-amino-alkane-sulfonic acids, containing ethane (TES), propane (TAPS), and butane (TABS); and the *N*-(morpholino)-alkane-sulfonic acids, containing ethane (MES), propane (MOPS), or butane (MOBS). In comparing the molecular structures of TAPS and MOPS with those of TAPSO and MOPSO, there is an extra OH group (on the β-carbon nearby the sulfonic group) on TAPSO and MOPSO, respectively. Thus, carefully performed measurements on these two sets of biological buffers could also be used to determine the effect of the methylene increment and the hydroxyl group on the interactions of these buffers with metal ions.

EXPERIMENTAL SECTION

Materials and Solutions. The biological buffers, TRIS (w > 0.999), TES (w > 0.99), TAPS (w > 0.995), TAPSO (w > 0.99), TABS (w > 0.99), MES (w > 0.99), MOPS (w > 0.995), MOPSO (w > 0.99), and MOBS (w > 0.99) were obtained from Sigma-Aldrich Chemical Co. Sodium hydroxide ($w \geq$ 0.98) was obtained from Acros Organics Co. A carbonate-free sodium hydroxide solution was prepared by dissolving sodium hydroxide pellets in ultra pure water, and the solution was standardized potentiometrically with potassium hydrogen phthalate (w > 0.99, Sigma-Aldrich). Nitric acid (Sigma-Aldrich, USA) solution ($\approx$ 0.03 mol·dm^{-3}) was prepared and used after being standardized. Chromium nitrate nonahydrate ($Cr(NO_3)_3\cdot 9H_2O$, w = 0.9999+) was obtained from Sigma-Aldrich Chemical Co. Potassium chloride (KCl, w = 0.9999+) was supplied by Acros Organics Co. All of the purchased materials were used without further purification. All solutions used throughout the experiments were prepared freshly in ultra pure water obtained from a NANO pure-Ultrapure water system with resistivity of 18.3 MΩ·cm. All of the aqueous solution samples were prepared gravimetrically.

Apparatus and Procedure. The pH measurements were carried out at 310.15 K using a tightly closed, jacketed equilibrium cell with volume 100 cm^3. Thermostatic water was circulated through the jacket of the equilibrium cell to control the cell's temperature to within ± 0.1 K. The cell's temperature was measured with a mercury thermometer calibrated by a precision

thermometer (model 1560, Hart Scientific Co.) to an uncertainty of ± 0.1 K. The cell is equipped with a magnetic stirrer. A constant ionic strength was maintained at 0.16 mol·dm^{-3} KCl, and a total volume 50 cm^3 was used for each titration. A HTC-210U pH meter using a glass electrode was used to monitor the pH changes. The pH meter was calibrated before each titration with pH 4.0 and 7.0 standard buffer solutions. The glass electrode was then calibrated in terms of hydrogen ion concentration by titrating HCl solutions with NaOH. The results of this potentiometric titration were analyzed using a computer program (GLEE, glass electrode evaluation),[19] which is included in HYPERQUAD suite programs. This program provides the pseudo-Nernstian standard potential and slope of the electrode. For all systems, monotonic titrant volume additions of standardized NaOH were made, and the pH changes were monitored through the pH meter as a function of the added volume. Each titration was repeated at least three times under carefully controlled experimental conditions in the pH range between 2.4 and 10.5. Typically, between 60 and 200 points (pH readings) were collected and taken into account for each titration. For the determination of the Cr(III) complexes with all buffers studied, the pH-potentiometric titrations were carried out using fixed total ligand to total metal-ion concentration ratios (T_L:T_{cr}) to fulfill the maximum coordination number of the metal ion.

Data Analysis. The determination of the protonation constants and the overall stability constants of the complex formation between Cr(III) and buffers were carried out using the HYPERQUAD program (Version 2008).[20] The species formed in the investigated systems were characterized by the general equilibrium:

$$p\mathrm{Cr(III)} + q\mathrm{L} + r\mathrm{H} \rightleftharpoons \mathrm{Cr}_p\mathrm{L}_q\mathrm{H}_r \quad (1)$$

and the formation constants β_{pqr} are defined as follows, with charges omitted for simplicity.

$$\beta_{\mathrm{pqr}} = \frac{[\mathrm{Cr}_p\mathrm{L}_q\mathrm{H}_r]}{[\mathrm{Cr}]^p[\mathrm{L}]^q[\mathrm{H}]^r} \quad (2)$$

where β_{pqr} represents the formation constants of the complex species with different three stoichiometric coefficients (p, q, r) given in the order Cr, H, L. The values of p and q are positive integers or zero, and r is positive for protonated species, or zero. A negative value for r refers to the hydroxo-complexes. $[\mathrm{Cr}_p\mathrm{L}_q\mathrm{H}_r]$ is the concentration of the complex species. [Cr] and [L] are concentrations of the free reactant species, and [H] is the measured proton concentration.

In HYPERQUAD calculations the overall stability constants ($\log \beta_{pqr}$) are varied to minimize the difference between calculated and observed values of pH. Additionally, HYPERQUAD allows simultaneous refinement of multiple data sets. For each experimental titration point, the equilibrium concentrations of the species in solutions are defined by the following mass balance equations:

$$T_{\mathrm{Cr}} = [\mathrm{Cr}] + \sum p\beta_{pqr}[\mathrm{Cr}]^p[\mathrm{L}]^q[\mathrm{H}]^r \quad (3)$$

$$T_{\mathrm{L}} = [\mathrm{L}] + \sum q\beta_{pqr}[\mathrm{Cr}]^p[\mathrm{L}]^q[\mathrm{H}]^r \quad (4)$$

$$T_{\mathrm{H}} = [\mathrm{H}] + \sum r\beta_{pqr}[\mathrm{Cr}]^p[\mathrm{L}]^q[\mathrm{H}]^r \quad (5)$$

where T_{Cr}, T_L, and T_H are the analytical concentrations of metal, ligand, and proton, respectively, and are known from the quantities used to make up the solutions. The unknown parameters are [Cr] and [L] for each titration point and the formation constants, β_{pqr}. The [H] is obtained from potentiometric titration. The ionic product of water (pK_w = 13.46 at 310.15 K and ionic strength I = 0.10 mol·dm^{-3} KCl)[21] was maintained constant during all refinements. The T_L:T_{Cr} ratios (1:1, 2:1, or 3:1) used to characterize Cr−(buffer)$_x$−(OH)$_y$ systems, as well as the pH range used in the refinement by the HYPERQUAD program, are presented in Table 1. During the titrations the solution remained clear within the reported pH ranges for each system. However, precipitation occurred beyond the reported pH ranges in that table. The selected model was the one that gave the best statistical fit and was chemically reasonable with the experimental pH data.

The HySS (HYPERQUAD Simulation and Speciation) program, a new program developed from the HYPHEN program[22] in the HYPERQUAD suite, was used to determine the speciation diagrams that would be obtained in a simulated titration, given a set of estimates for the overall stability constants and titration conditions.

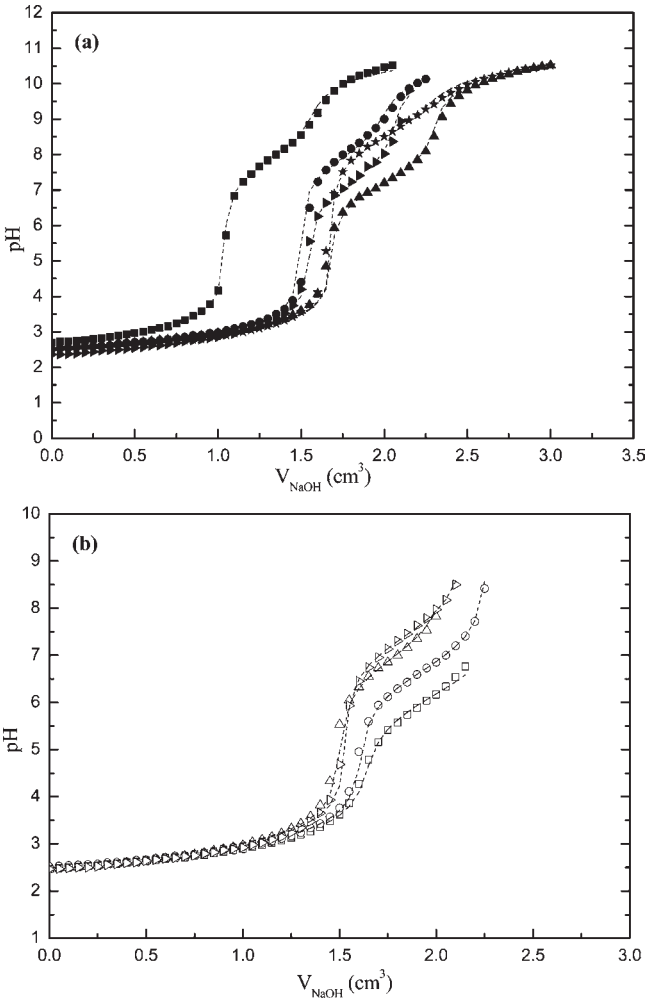

Figure 1. pH titration curves of TRIS family (a) and morpholine family (b) at [T_L] = 1·10^{-3} mol·dm^{-3}; I = 0.16 mol·dm^{-3} KCl and 310.15 K. The dashed lines are the calculated pH from the refinement operations. The symbols: ■, TRIS; ▲, TES; ●, TAPS; solid right-pointing triangle, TAPSO; ★, TABS; □, MES; △, MOPS; ○, MOPSO; and open right-pointing triangle, MOBS.

dx.doi.org/10.1021/je200345a |J. Chem. Eng. Data 2011, 56, 3541–3551

Scheme 1. Protonation Equilibria of TRIS and TES Buffers

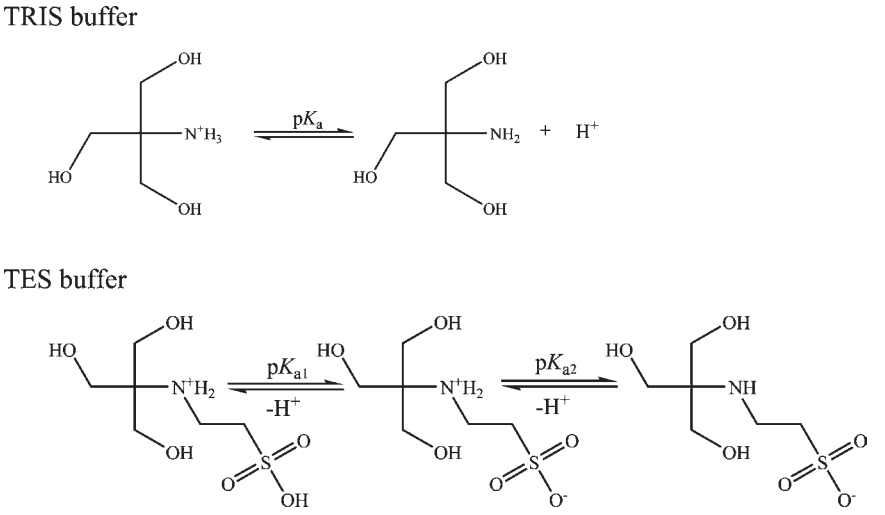

Table 2. Protonation Constants of the Buffers in Water at 310.15 K and Ionic Strength I = 0.16 mol·dm^{-3} KCl and Literature Data

ligand	pK_a	pK_{a2}	SD
TRIS	7.81 (7.80)[a]		0.0254
TES		7.09 (7.08)[b]	0.0292
TAPS		7.91 (7.98)[b]	0.0269
TAPSO		7.27 (7.3757)[c]	0.0553
TABS		8.41 (8.539)[d]	0.0341
MES		5.99 (5.96)[b]	0.0310
MOPS		7.02 (7.044)[c]	0.0369
MOPSO		6.66 (6.698)[c]	0.0295
MOBS		7.41 (7.533)[e]	0.0308

[a] Reference 23, T = 308.15 K, and I = 0.0 mol·dm^{-3}. [b] Reference 23, T = 310.15 K, and I = 0.16 mol·dm^{-3}. [c] Reference 23, T = 310.15 K, and I = 0.0 mol·dm^{-3}. [d] Reference 24, T = 310.15 K, and I = 0.0 mol·dm^{-3}. [e] Reference 25, T = 310.15 K, and I = 0.0 mol·dm^{-3}.

RESULTS AND DISCUSSION

Protonation Equilibria. The buffers TES, TAPS, TAPSO, TABS, MES, MOPS, MOPSO, and MOBS are zwitterionic buffers with two pK_a's. The first dissociation constant (pK_{a1}) refers to the dissociation of the sulfonic group, while the second one is due to dissociation of a proton on the amino group (pK_{a2}). TRIS buffer has only one pK_a, which represents the dissociation constant of the amino group. Typically fitted profiles of the experimental titration curves of TRIS and the zwitterionic buffers using HYPERQUAD 2008 program are shown in Figure 1.

The (acid + base) equilibria of TRIS and a zwitterionic buffer (i.e., TES) can be represented by the following Scheme 1.

At first, we intended to find both protonation constants of the zwitterionic buffers, but the pK_{a1} values of these buffers are too low and exist only in strongly acidic solutions.[15] Thus, it is difficult to determine the exact value of pK_{a1}, since the pH-metric data are measured in the pH range 2.40 to 10.50. The determined dissociation constant of TRIS and the pK_{a2} of the zwitterionic buffers using the HYPERQUAD 2008 program and the standard deviation are reported in Table 2 together with the values obtained from previous investigations.[23−25] To our knowledge, the pK_{a2} values of TES, TAPS, and MES at T = 310.15 K and I = 0.16 were only found in literature.[23] The pK_{a2} values obtained from this work agree well with the literature values. However, the pK_{a2} values of other buffers at the same condition are nowhere to be found in literature. For comparison purposes, the pK_{a2} values of these buffers were compared with those of published data[24,25] at a relatively close experimental condition.

From the inspection of the reported data in Table 2, two main effects on the acidity of the protonated ligands can be indicated. First, the insertion of methylene groups separating the sulfonate group from the remaining portion of the molecule causes an increase of the pK_a values. The pK_{a2} values of the zwitterionic buffers in the order TABS > TAPS > TES and MOBS > MOPS > MES for TRIS and morpholine families, respectively. The results can be explained in terms of the field effect of the methylene groups, which results in an increase of the electron density on the nitrogen atom. Second, the insertion of a hydroxyl group on the β-carbon nearby the sulfonic group of TAPSO and MOPSO molecules causes a relevant lowering of pK_{a2} values than those of TAPS and MOPS, respectively. This result can be attributed to either intramolecular hydrogen bond formation,[26−28] which is stronger in the deprotonated form than in the protonated one, or the negative inductive (electron-withdrawing polar) effect from the hydroxy group.

Complexation Equilibria. A series of potentiometric titration for the Cr(III)-buffer (L) systems were performed between pH 2.4 and 10.5 at three different ligand-to-metal molar ratios (1:1, 2:1, and 3:1) at 310.15 K and I = 0.16 mol·dm^{-3} KCl. Representative potentiometric titration curves are shown in Figure 2 for all buffers in the presence of Cr(III) at the 2:1 ligand-to-metal molar ratio. The equilibrium models for Cr(III)-buffer systems and corresponding overall stability constants (log β_{pqr}) giving the best fits of the pH-metric titration curves are summarized in Table 3. The reported standard deviations are calculated by the HYPERQUAD program, based on the ranges in the stability constants obtained for the same model refined from several independent titrations.

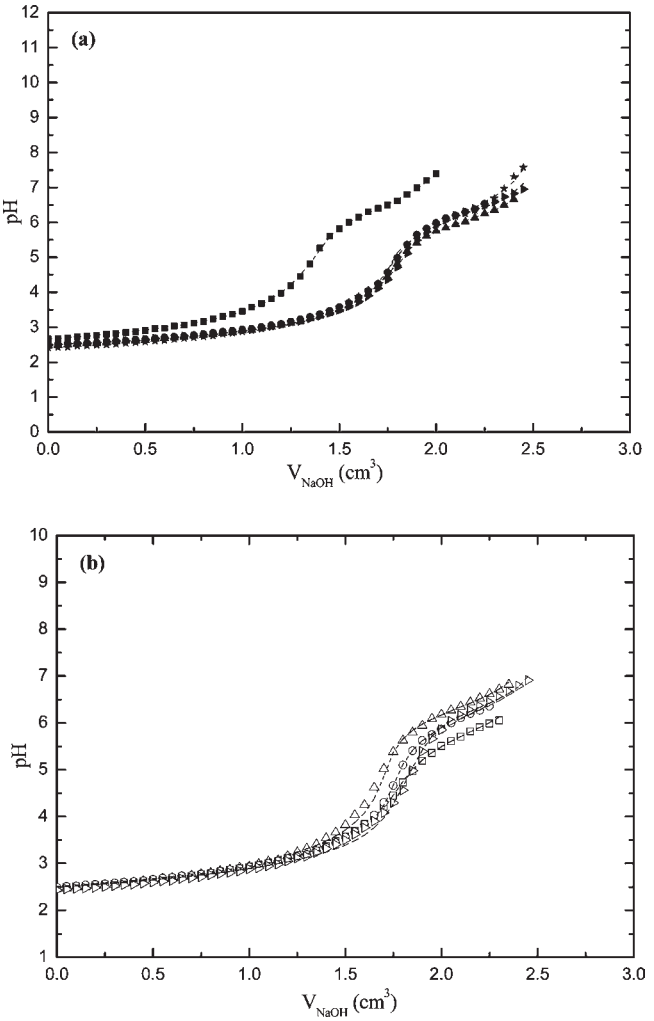

Figure 2. pH titration curves of Cr(III) with TRIS family (a) and morpholine family (b) at $[T_L]$:$[T_{Cr}]$ = 2:1; $[T_{Cr}] = 5 \cdot 10^{-4}$ mol·dm^{-3}; I = 0.16 mol·dm^{-3} KCl and 310.15 K. The dashed lines are the calculated pH from the refinement operations. The symbols: ■, TRIS + Cr(III); ▲, TES + Cr(III); ●, TAPS + Cr(III); solid right-pointing triangle, TAPSO + Cr(III); ★, TABS + Cr(III); □, MES + Cr(III); △, MOPS + Cr(III); ○, MOPSO + Cr(III); and open right-pointing triangle, MOBS + Cr(III) systems.

Complexation Equilibria of Cr(III) with TRIS Family. The best fit of the titration data by the HYPERQUAD program indicates that five species of Cr−(L)$_x$−(OH)$_y$ complexes exist in solution during the titration, where L = TRIS, TES, TAPS, TAPSO, and TABS. These five complexes are CrL, CrL$_2$, CrL$_2$(OH), CrL$_2$(OH)$_2$, and CrL$_3$. Similar species have been reported for other M−(buffer)$_x$−(OH)$_y$ systems.[29−32] Despite the fact that the log β_{pqr} constant expresses the stability of the CrL$_x$ binary-ligand complexes, it does not represent directly the binding strength between buffer and Cr(III). The stepwise stability constants, log K_1, log K_2, and log K_3, derived from the computed values of log β_{pqr}, according to equations: log K_1 = log β_{110}, log K_2 = log β_{120} − log K_1, and log K_3 = log β_{130} − log K_2, show how tightly buffer ligand is bound to the Cr(III) ion (Table 4). In addition, it can be seen that log K_3 values are lower than those of log K_2, and the stability constants of the latter complexes are lower than those of the log K_1, as expected from the steric hindrance effect. The stepwise equilibria corresponding to the stability constants log K_1, log K_2, and log K_3 can be represented as follows:

$$\mathrm{Cr} + \mathrm{L} \rightleftharpoons \mathrm{CrL} \qquad K_1 = \frac{[\mathrm{CrL}]}{[\mathrm{Cr}][\mathrm{L}]} \tag{6}$$

$$\mathrm{CrL} + \mathrm{L} \rightleftharpoons \mathrm{CrL_2} \qquad K_2 = \frac{[\mathrm{CrL_2}]}{[\mathrm{CrL}][\mathrm{L}]} \tag{7}$$

$$\mathrm{CrL_2} + \mathrm{L} \rightleftharpoons \mathrm{CrL_3} \qquad K_3 = \frac{[\mathrm{CrL_3}]}{[\mathrm{CrL_2}][\mathrm{L}]} \tag{8}$$

The following order of complexation is mainly found: TABS > TAPSO > TRIS > TAPS > TES. The ligands TABS, TAPS, and TES show a decrease in the complex strength, as expected from the variation of amine group basicity due to the field effect discussed previously in the protonation equilibria section. It is then presumed that the coordination for those buffers occurs mainly by means of the amino group, but for TAPSO and TRIS, this was not the case. TRIS forms chelates with transition metal via the amino group and one or two hydroxymethyl groups.[33] The stability of the binary complexes involving TRIS is higher than that of the complexes containing TAPS. This behavior does not follow the basicities as expected. Probably TRIS acts as a tridentate ligand, whereas TAPS acts as a bidentate ligand with Cr(III) in aqueous solution. The stepwise stability constants of TAPSO with Cr(III) are higher than those of TAPS, suggesting that the TAPSO's hydroxyl group near the sulfonic group is involved in the coordination. This is in agreement with earlier observation on the complexation of TAPSO and TAPS with different metal ions.[29] Consequently, TAPS can act as a bidentate ligand through the amino group and one of the hydroxy groups, forming one five-membered chelate ring. Meanwhile, TAPSO is the most likely tridentate ligand chelates via the amino group and by two hydroxyl groups, forming two five-membered chelate rings.[29]

The distribution diagrams of species (DDS) were computed with the HySS program for the Cr(L)$_x$(OH)$_y$ system at 3:1 ligand-to-metal molar ratio as a function of pH and are presented in Figures 3 and 4. The analysis of DDS for Cr(TRIS)$_x$(OH)$_y$ system (Figure 3a) shows that, up to ca. pH 5, only a simple species are formed: $[Cr(TRIS)]^{3+}$ and $[Cr(TRIS)_2]^{3+}$. The latter species starts to form at ca. pH 3 and dominates in the solution above pH 5. The formation of $[Cr(TRIS)_3]^{3+}$ and $[Cr(TRIS)_2(OH)]^{2+}$ starts at ca. pH 5, and it is predominant in the solution at ca. pH 7 and begins to be negligible at pH 9 onward. $[Cr(TRIS)_2(OH)_2]^{+}$ begins to be significant from ca. pH 6 onward, reaching a maximum concentration of 99 %, at pH = 8.8. The diagram clearly displays the amount of each species in the buffering range. The physiological pH range of TRIS is between 7.0 and 9.0.[27] The DDS for the Cr(TES)$_x$(OH)$_y$ system (Figure 3b) evidence that the dominating complex at lower pH values is the $[Cr(TES)]^{2+}$, with the maximum concentration of 85 % at pH = 4. As can be seen from Figure 3b, in going from acidic to weakly alkaline medium, the gradual formation of complexes $[Cr(TES)_2]^{+}$ and $[Cr(TES)_3]$ takes place. The concentration of the $[Cr(TES)_2(OH)]$ species is low with maximum of ca. 12 % in the pH range (4.5 to 8.5). The $[Cr(TES)_2(OH)_2]^{-}$ species starts to form above pH 5 and reaches a maximum concentration (ca. 99 %) at pH 8.2. TAPS buffer has an effective pH range between 6.0 and 8.2. The DDS

dx.doi.org/10.1021/je200345a |J. Chem. Eng. Data 2011, 56, 3541–3551

Table 3. Overall Stability Constants ($\log \beta_{pqr}$) for Cr(III) Complexes with TRIS and Morpholine Families at 310.15 K and I = 0.16 mol·dm^{-3} KCl

TRIS family				morpholine family			
species	(p,q,r)	$\log \beta_{pqr}$	SD	species	(p,q,r)	$\log \beta_{pqr}$	SD
	TRIS				MES		
$[CrL]^{3+}$	(1, 1, 0)	7.63	0.0303	$[CrL]^{2+}$	(1, 1, 0)	5.79	0.0521
$[CrL_2]^{3+}$	(1, 2, 0)	13.63	0.0448	$[CrL_2]^{+}$	(1, 2, 0)	9.88	0.1106
$[CrL_2(OH)]^{2+}$	(1, 2, −1)	6.78	0.0505	$[CrL_2(OH)]$	(1, 2, −1)	4.15	0.1435
$[CrL_2(OH)_2]^{+}$	(1, 2, −2)	0.26	0.0431	$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	−1.59	0.0801
$[CrL_3]^{3+}$	(1, 3, 0)	18.39	0.0502				
	TES				MOPS		
$[CrL]^{2+}$	(1, 1, 0)	7.35	0.0311	$[CrL]^{2+}$	(1, 1, 0)	6.80	0.0523
$[CrL_2]^{+}$	(1, 2, 0)	12.51	0.0456	$[CrL_2]^{+}$	(1, 2, 0)	11.40	0.0615
$[CrL_2(OH)]$	(1, 2, −1)	6.05	0.1200	$[CrL_2(OH)]$	(1, 2, −1)	4.57	0.0454
$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	0.21	0.0435	$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	−1.15	0.0903
$[CrL_3]$	(1, 3, 0)	17.18	0.0570				
	TAPS				MOPSO		
$[CrL]^{2+}$	(1, 1, 0)	7.51	0.0842	$[CrL]^{2+}$	(1, 1, 0)	6.55	0.0340
$[CrL_2]^{+}$	(1, 2, 0)	12.78	0.0613	$[CrL_2]^{+}$	(1, 2, 0)	10.83	0.0920
$[CrL_2(OH)]$	(1, 2, −1)	5.92	0.0724	$[CrL_2(OH)]$	(1, 2, −1)	4.75	0.0901
$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	−0.53	0.0587	$[CrL_2(OH)_2]^{-}$	(1, 2, 2)	−1.34	0.0521
$[CrL_3]$	(1, 3, 0)	17.46	0.1140				
	TAPSO				MOBS		
$[CrL]^{2+}$	(1, 1, 0)	7.88	0.0483	$[CrL]^{2+}$	(1, 1, 0)	7.91	0.0333
$[CrL_2]^{+}$	(1, 2, 0)	14.11	0.0451	$[CrL_2]^{+}$	(1, 2, 0)	13.61	0.0410
$[CrL_2(OH)]$	(1, 2, −1)	8.50	0.0691	$[CrL(OH)_2]$	(1, 2, −1)	7.10	0.0509
$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	2.25	0.0654	$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	0.99	0.0780
$[CrL_3]$	(1, 3, 0)	19.46	00705	$[CrL_3]$	(1, 3, 0)	18.08	0.1335
	TABS						
$[CrL]^{2+}$	(1, 1, 0)	8.50	0.0647				
$[CrL_2]^{+}$	(1, 2, 0)	14.77	0.0911				
$[CrL_2(OH)]$	(1, 2, −1)	8.44	0.0861				
$[CrL_2(OH)_2]^{-}$	(1, 2, −2)	1.66	0.0984				
$[CrL_3]$	(1, 3, 0)	20.59	0.0945				

Table 4. Stability Constants for Cr(III) Binary Complexes in Aqueous Media at 310.15 K and I = 0.16 mol·dm^{-3} KCl

ligand	$\log K_1$	$\log K_2$	$\log K_3$
TRIS	7.63	6.00	4.76
TES	7.35	5.16	4.55
TAPS	7.51	5.27	4.68
TAPSO	7.88	6.23	5.35
TABS	8.50	6.27	5.82
MES	5.79	4.09	
MOPS	6.80	4.60	
MOPSO	6.55	4.28	
MOBS	7.91	5.70	4.47

for the $Cr(TAPS)_x(OH)_y$ system (Figure 3c) indicates that, in the buffering pH range of TAPS (7.7 to 9.1), minor amounts of the $[Cr(TAPS)_3]$ and $[Cr(TAPS)_2(OH)]$ species exist with negligible concentrations of $[Cr(TAPS)_2]^+$, while the major species is $[Cr(TAPS)_2(OH)_2]^-$ (ca. 87 %) at pH 7.7 and reaches the maximum concentration (ca. 99 %) at pH 8.7. The maximum concentration of $[Cr(TAPS)]^{2+}$ (ca. 87 %), $[Cr(TAPS)_2]^+$ (ca. 42 %), and $[Cr(TAPS)_3]$ (ca. 20 %) species is formed, respectively, at pH 4.7, 6.0, and 6.7, whereas in the $Cr(TAPSO)_x(OH)_y$ system (Figure 3d) the maximum concentration of the analogous species is formed at pH 3.4, 4.8, and 6.0, respectively. Minor amounts from $[Cr(TAPSO)_3]$ and $[Cr(TAPSO)_2(OH)]$ species with a negligible amount of $[Cr(TAPSO)_2]^+$ have also been observed in pH range (7.0 to 8.2), the physiological pH range of TAPSO. The concentration of the $[Cr(TAPS)_2(OH)_2]^-$ species is ca. 74 % at pH 7.0 and reaches a maximum of ca. 99 % in the pH 8.2. Figure 3e shows that the $[Cr(TABS)_2(OH)_2]^-$ species is the dominating species (ca. 92.0 to 99.7 %) present in solution at the buffering range of TABS (8.2 to 9.6).

Complexation Equilibria of Cr(III) with Morpholine Family. The potentiometric refinement was quite successful using the model consisting of CrL, CrL_2, $CrL_2(OH)$, and $CrL_2(OH)_2$ species, where L = MES, MOPS, MOPSO, and MOBS.

dx.doi.org/10.1021/je200345a |J. Chem. Eng. Data 2011, 56, 3541–3551

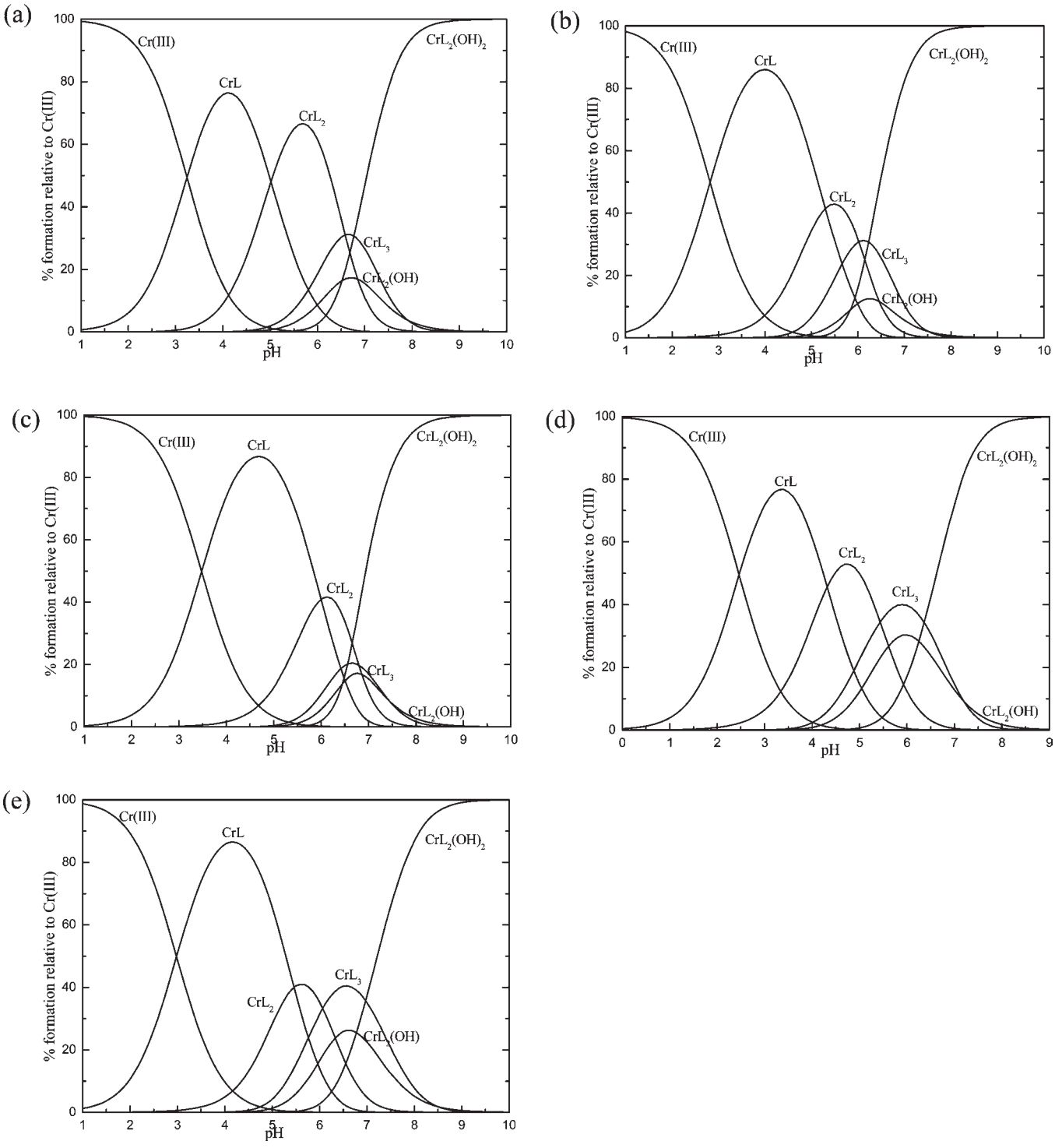

Figure 3. Species-distribution diagrams of Cr(III) with (a) TRIS, (b) TES, (c) TAPS, (d) TASO, and (e) TABS; $[T_L]$:$[T_{Cr}]$ = 3:1 at $[T_{Cr}]$ = $3 \cdot 10^{-4}$ mol·dm^{-3}; I = 0.16 mol·dm^{-3} KCl and 310.15 K. For sake of simplicity, the charges are omitted.

Additionally, the refinement of the titration data of the Cr(III)MOBS system evidenced the formation of CrL_3 species. The stabilities of the binary complexes of MES, MOPS, MOPSO, and MOBS (Table 3) appear to follow the same order as their basicities, that is, MOBS > MOPS > MOPSO > MES. It was found that the stabilities of the morpholine family complexes are lower than those of TRIS family complexes, as a result of large difference in their basic strengths. It is also suggested that the possibility of the terminal hydroxy groups of TRIS family buffers to be involved in the coordination is responsible for the higher stability of their binary complexes.

The above-mentioned buffers are useful for pH control in the physiological region of 5.5 to 6.7 for MES, 6.5 to 7.9 for MOPS, 6.2 to 7.6 for MOPSO, and 6.9 to 8.3 for MOBS, respectively.

dx.doi.org/10.1021/je200345a |J. Chem. Eng. Data 2011, 56, 3541–3551

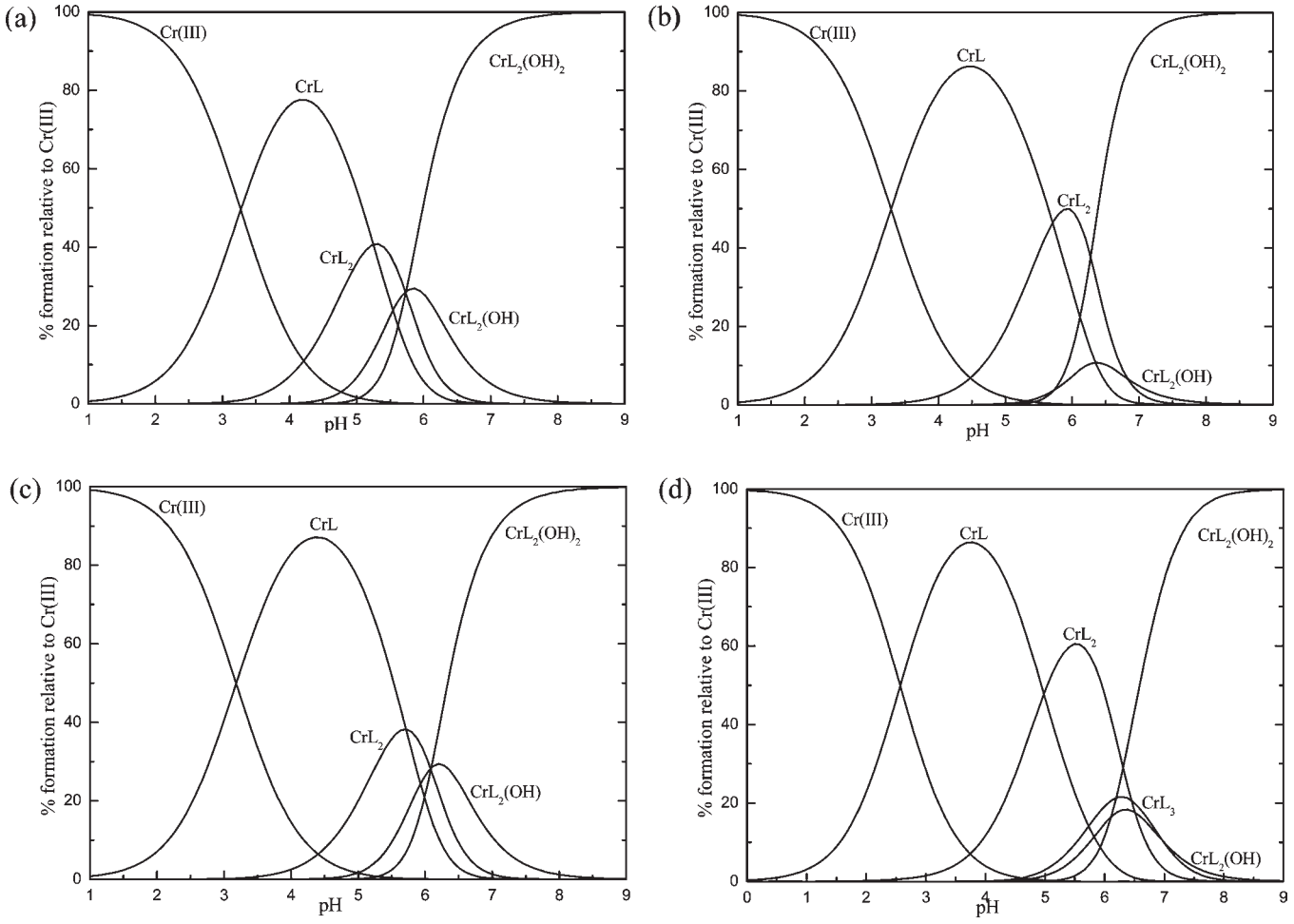

Figure 4. Species-distribution diagrams of Cr(III) with (a) MES, (b) MOPS, (c) MOPSO, and (d) MOBS; $[T_L]$:$[T_{Cr}]$ = 3:1 at $[T_{Cr}] = 3 \cdot 10^{-4}$ mol·dm^{-3}; I = 0.16 mol·dm^{-3} (KCl) and 310.15 K. For sake of simplicity, the charges are omitted.

The DDS gives a clear picture of the complexes that formed with these buffers in their respective buffering range. It can be clearly seen that the DDS of $Cr(MES)_x(OH)_y$, $Cr(MOPS)_x(OH)_y$, and $Cr(MOPSO)_x(OH)_y$ systems are similar as shown in Figure 4a−c. Throughout this figure, the formation of $[CrL]^{2+}$ and $[CrL_2]^{+}$ takes place, respectively, in pH ranges ca. (1 to 7) and (3 to 7), while the formation of the $[CrL_2(OH)]$ complex is observed in pH range ca. (5 to 9) (L = MES, MOPS, and MOPSO). Above pH 5, the $[CrL_2(OH)_2]^{-}$ complex starts to form and reaches maximum concentration (ca. 99 %) at pH 8.0. The analysis of DDS for the $Cr(MOBS)_x(OH)_y$ system (Figure 4d) shows that $[Cr(MOBS)_2(OH)_2]^{-}$ is the dominating species (ca. 88 to 99 %) present in solution at the buffering range of MOBS (6.9 to 8.3), whereas both $[Cr(TRIS)]^{3+}$ and $[Cr(TRIS)_2]^{3+}$ species are formed before the buffering region. In the pH range (4 to 8), the two species $[Cr(MOBS)_2(OH)]$ and $[Cr(MOBS)_3]$ are present together.

Contribution of CH_2 and OH on Complexation. To estimate the Δ log K_1 values of CH_2 groups, we have subtracted the corresponding (log K_1) values of buffers, as shown in Figure 5a, which designates two types of mathematical constructs. First, the simple subtractional constructs consist of subtracting the log K_1 values of two buffers, such as [(TAPS − TES) or (TABS − TAPS)] from the TRIS family and [(MOPS − MES) or (MOBS − MOPS)] from the morpholine family. Second, the composite constructs are calculated by subtracting the log K_1 values of two buffers that differ in chain length by more constructs of one CH_2 group, such as TABS and TES, then dividing by two, such as the difference of the numbers of the CH_2 group between TABS and TES, [(TABS − TES)/2], from the TRIS family. Calculations were done similarly for other two different chain length buffers of morpholine family, such as [(MOBS − MES)/2]. On the other hand, we calculated the OH (on the β-carbon nearby the sulfonic group) group contributions by the subtraction of log K_1 of TAPSO and MOSPO from those of TAPS and MOPS, respectively, as represented in Figure 5b.

The results in Table 5 reveal that the Δ log K_1 values of the CH_2 group are positive. The positive contribution indicates that the insertion of methylene groups between the amino group and sulfonic group enhanced the complexation. It is interesting to note that the Δ log K_1 values of the CH_2 group calculated by the simple subtractional and composite constructs of morpholine family are almost same, that is, Δ log K_1 = ~1.0, whereas those obtained from TRIS family have different values. The results indicate that the terminal hydroxyl groups of the TRIS family contribute to the coordination. On the other hand, the coordination of morpholine family probably occurs mainly via the amino group. The Δ log K_1 value of (TAPSO − TAPS) is positive, indicating participation of the OH group of TAPSO in coordination. In contrast, the values of (MOPSO − MOPS) are negative,

dx.doi.org/10.1021/je200345a |J. Chem. Eng. Data 2011, 56, 3541–3551

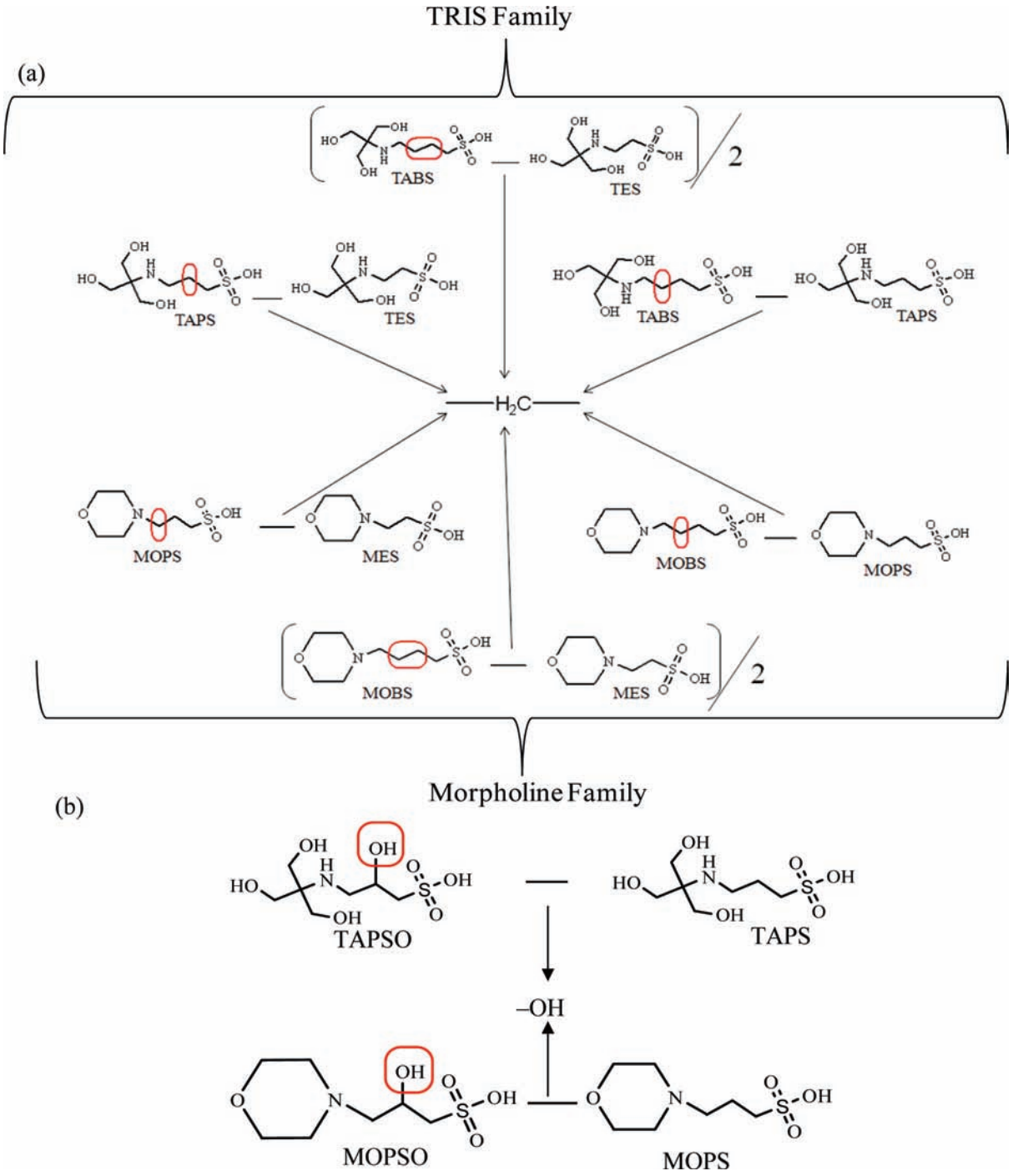

Figure 5. Schematic illustration of the contribution of CH_2 and OH groups. (a) The simple subtractional and composite mathematical constructs for estimating the $\Delta \log K_1$ value of the CH_2 group from the TRIS family (upper part) and morpholine family (lower part). (b) The subtraction of $\log K_1$ of TAPSO and MOSPO from those of TAPS and MOPS, respectively, for estimating the $\Delta \log K_1$ value (OH).

Table 5. Contribution of CH_2 and OH Groups ($\Delta \log K_1$) in Aqueous Media at 310.15 K and I = 0.16 mol·dm^{-3} KCl

	$\Delta \log K_1$							
	TRIS family				morpholine family			
group	TAPS − TES	TABS − TAPS	(TABS − TES)/2	TAPSO − TAPS	MOPS − MES	MOBS − MOPS	(MOBS − MES)/2	MOPSO − MOPS
CH_2	0.16	0.99	0.58		1.01	1.10	1.06	
OH				0.37				−0.25

dx.doi.org/10.1021/je200345a |J. Chem. Eng. Data 2011, 56, 3541–3551

which indicates that the OH group of MOPSO may not be taking part in coordination with the metal ion.

CONCLUSIONS

In this work, the interactions between Cr(III) and some important biological buffers (TRIS, TES, TAPS, TAPSO, TABS, MES, MOPS, MOPSO, and MOBS) were studied at 310.15 K and ionic strength I = 0.16 mol·dm^{-3} KCl by using the potentiometry technique. The results indicate that all studied buffers form complexes with Cr(III). Therefore, when these buffers are used in studies where this metal ion exists, interference can occur due to the complex formation. The overall stability constants have been obtained by the HYPERQUAD 2008 program for the following species: CrL, CrL_2, $CrL_2(OH)$, $CrL_2(OH)_2$, and CrL_3, where L = TRIS, TAPS, TAPSO, TABS, and MOBS. The first four species have also obtained for MES, MOPS, and MOPSO. The following order of complexation is mainly found: TABS > TAPSO > TRIS > TAPS > TES and MOBS > MOPS > MOPSO > MES for the TRIS family and morpholine family, respectively. The stabilities of the TRIS family complexes are greater than those of morpholine family complexes. An evaluation of the effects of CH_2 and OH (nearby the sulfonic group) groups on the stability of the binary systems has been studied. It was found that the insertion of the CH_2 groups between the zwitterions enhanced the stability constant. The OH group of TAPSO may participate in coordination, while the OH group of MOPSO may not be taking part in coordination with Cr(III) ion.

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Funding Sources

The authors are grateful for financing provided by the National Science Council, Taiwan, through Grant No. NSC97-2214-E-011-049-MY3 and NSC99-2811-E-011-023.

ACKNOWLEDGMENT

The authors thank Dr. Ho-mu Lin for valuable discussions.

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