

Hexadentate N₄O₂ Amine Phenol Complexes of Gallium and IndiumErnest Wong,¹ Shuang Liu,² Thomas Lügger,³ F. Ekkehardt Hahn,^{*,3} and Chris Orvig^{*,1}

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Several linear N₄O₂ amine phenols based on triethylenetetramine (trien) were prepared and characterized by spectroscopic techniques (H₂bad = 1,10-bis(2-hydroxybenzyl)-1,4,7,10-tetraazadecane; H₂Clbad = 1,10-bis(2-hydroxy-5-chlorobenzyl)-1,4,7,10-tetraazadecane; H₂Brbad = 1,10-bis(2-hydroxy-5-bromobenzyl)-1,4,7,10-tetraazadecane). These amine phenols were prepared by the *in situ* reduction of the corresponding Schiff bases, which were in turn derived from condensation reactions of trien with the appropriately substituted salicylaldehyde. Characterization of the amine phenols revealed two hydroxybenzyl groups connected to the trien backbone via the terminal primary amine nitrogen atoms. There are six potential sites for coordination to a metal ion: four amine nitrogens and two phenolate oxygens. Acetone adducts, prepared by refluxing the amine phenols in acetone, contained two imidazolidine rings, each of which was formed by the reaction of acetone with one inner and one terminal amine nitrogen. Monocationic metal complexes were obtained from the reactions of Ga³⁺ and In³⁺ with the N₄O₂ amine phenols in the presence of 2 equiv of base (acetate). The molecular structure of [Ga(Brbad)]ClO₄·(CH₃)₂SO (C₂₂H₃₂Br₂ClGaN₄O₇S, MW = 761.6) was determined by X-ray methods: orthorhombic space group *Pbca*; *a* = 14.777(4), *b* = 22.221(5), *c* = 17.410(7) Å; *V* = 5717(5) Å³, *Z* = 8. The structure was solved by the Patterson method and was refined by full-matrix least squares procedures to *R* = 4.81%, *R_w* = 5.22% for 2230 reflections with *F_o*² ≥ 3σ(*F_o*²). Ga³⁺ was coordinated by four neutral amine nitrogens and two anionic phenolate oxygens to give an N₄O₂ donor set in a distorted octahedral geometry. The two phenolate oxygen atoms and each pair of sequential N donor atoms were coordinated *cis* to each other. The perchlorate anion suffers from a 2-fold disorder around a pseudo-3-fold O–Cl axis, and there is a DMSO solvate molecule. ¹H NMR spectral data of the metal complexes showed rigid solution structures for all the Ga and In complexes; no evidence of fluxional behavior was observed at solution temperatures as high as 120 °C.

Introduction

There is currently considerable interest in the coordination chemistry of the trivalent group 13 metal ions; this biomedical interest originates from the association of Al³⁺ with neurological disorders such as Alzheimer's disease⁴ and from the incorporation of Ga³⁺ and In³⁺ radionuclides (⁶⁷Ga, ⁶⁸Ga, and ¹¹¹In) into diagnostic radiopharmaceuticals.^{5–7} These radionuclides have nuclear properties that are suitable to the detection methods of diagnostic nuclear medicine (⁶⁷Ga, *t*_{1/2} = 78.1 h, *E_γ* = 93.3, 185, 300 keV; ⁶⁸Ga, *t*_{1/2} = 68 min, *E_γ* = 511 keV from β⁺ annihilation; ¹¹¹In, *t*_{1/2} = 67.5 h, *E_γ* = 172.5, 247 keV). Arising from this application is a directed approach to the coordination chemistry of, and ligand design for, these metal ions. The designed ligand should direct the metallic radionuclide to desired *in vivo* sites and/or impart desired *in vivo* properties to the resulting metal complexes. Research in our group has been concerned with the coordination of polydentate ligands to group

13 and lanthanide metal ions.^{8–13} Polydentate ligands are of great interest because their binding selectivity can be altered subtly by having the ligand either enforce a specific spatial arrangement of donor atoms (i.e. preorganization of the donor atoms) or incorporate a set of donor atoms tailored to the metal of interest. In addition, polydentate ligands have the potential to form complexes of high stability and slow ligand exchange kinetics. This is important in preventing rapid demetalation or complex decomposition if the ligand is to direct the radionuclide to the target organ or if the ligand is to be used as an effective chelating agent for the treatment of metal overload.

We recently reported Al, Ga, and In complexes with several series of tripodal polydentate amine phenol ligands which differed in tripodal backbone size (Chart 1): tris(2-aminoethyl)amine (tren) based potentially N₄O₃ amine phenols, **I**;⁸ 1,1,1-tris(aminomethyl)ethane (tame) based potentially N₃O₃ amine phenols, **II**;⁹ and 1,2,3-triaminopropane (tap) based potentially N₃O₃ amine phenols, **III**.¹⁰ Lanthanide complexes with N₄O₃ amine phenols **I** were also reported.^{11,12} Amine phenols are versatile polydentate ligands which provide potential coordination sites via both neutral amine nitrogen atoms and anionic phenolate oxygen atoms. Compared to the CH=N linkages in

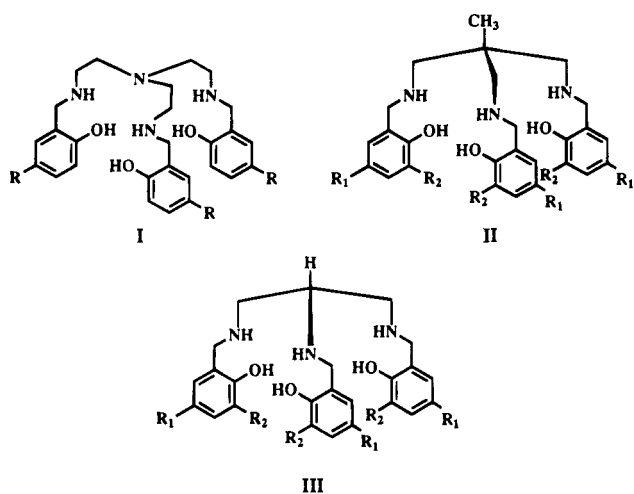
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- (4) (a) Perl, D. P. *Environ. Health Perspect.* **1985**, *63*, 149. (b) Crapper-McLachlan, D. R. *Neurobiol. Aging* **1986**, *7*, 525. (c) Liss, L. *Aluminum Neurotoxicity*; Pathotox Publishers: Park Forest, IL, 1980.
- (5) Welch, M. J.; Moerlein, S. M. In *Inorganic Chemistry in Biology and Medicine*; Martell, A. E., Ed.; American Chemical Society: Washington, DC, 1980; p 121.
- (6) Green, M. A.; Welch, M. J. *Nucl. Med. Biol.* **1989**, *16*, 435.
- (7) Clevette, D. J.; Orvig, C. *Polyhedron*. **1990**, *9*, 151.

- (8) Liu, S.; Rettig, S. J.; Orvig, C. *Inorg. Chem.* **1992**, *31*, 5400.
- (9) Liu, S.; Wong, E.; Karunaratne, V.; Rettig, S. J.; Orvig, C. *Inorg. Chem.* **1993**, *32*, 1756.
- (10) Liu, S.; Wong, E.; Rettig, S. J.; Orvig, C. *Inorg. Chem.* **1993**, *32*, 4268.
- (11) Liu, S.; Gelmini, L.; Rettig, S. J.; Thompson, R. C.; Orvig, C. *J. Am. Chem. Soc.* **1992**, *114*, 6081.
- (12) Liu, S.; Yang, L.-W.; Rettig, S. J.; Orvig, C. *Inorg. Chem.* **1993**, *32*, 2773.
- (13) Caravan, P.; Liu, S.; Orvig, C. Manuscript in preparation.

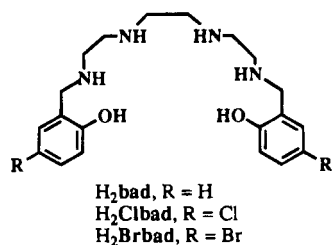
Chart 1



Schiff base compounds, the CH₂—NH linkages in the amine phenols are inert to hydrolytic decomposition and also provide a greater overall flexibility to the ligand. This increased flexibility allows the ligand to adjust to the demands of the metal ion and hence to contribute to the overall higher stability of the metal complex. Lipophilicity of the metal amine phenol complexes can be easily modified by varying the substituents on the aromatic rings. This approach allows the coordination environment of the metal to be maintained, while potentially altering the overall charge of the complex and the biodistribution of the complex.

The coordination behavior of group 13 metal ions with the tripod amine phenols I—III is affected by the electronic and steric demands of the metal ions, as well as by the flexibility of the amine phenol ligand. For example, the N₄O₃ amine phenols I coordinate to the hard Al³⁺ ion through an N₃O₃ donor atom set forming a cationic complex, while the Ga³⁺ ion is coordinated through an N₄O₂ donor set (also forming a cation) and the softer and larger In³⁺ ion through all seven N₄O₃ donor atoms to form a neutral complex.⁸ Studies of the coordination of Al³⁺, Ga³⁺, and In³⁺ with the more flexible tame-based II and tap-based III amine phenols revealed both series of amine phenols coordinate to the metal ion through all six coordination sites (N₃O₃ donor set);^{9,10} however, structural data suggested that the tame-based amine phenols II are more suitable for Al³⁺ and the tap-based amine phenols III are more suitable for Ga³⁺. The suitability of ligands for coordination with Al³⁺, Ga³⁺, and In³⁺ should be reflected in pM values (pM = -log [Mⁿ⁺]) and in observed stability constants. Preliminary work has shown that stability constants and pM values of metal complexes with tren-based N₄O₃ amine phenols I are much higher for Ga and In than for Al.¹³ This suggests that tren-based amine phenols I are more suitable for the larger Ga³⁺ and In³⁺ ions.

To broaden the investigation into the coordination of polydentate ligands more for lower group 13 metal ions, we present the coordination of Ga³⁺ and In³⁺ to a new series of potential N₄O₂ amine phenols (H₂bad, H₂Clbad, H₂Brbad) based on



triethylenetetramine (tren). Coordination of tren-based N₄O₂ amine phenols to Ga³⁺ and In³⁺ will most likely yield hexacoordinated monocationic complexes. Previous studies involving the coordination of Al³⁺, Ga³⁺, and In³⁺ with tren-based N₄O₂ Schiff base analogs revealed stable monocationic complexes^{14,15} which were recently shown to have potential as myocardial imaging agents.¹⁶ These earlier studies are encouraging, as Ga and In amine phenol complexes should be more stable than the corresponding Schiff base complexes, while possibly retaining similar biodistribution patterns.

Experimental Section

Materials. Triethylenetetramine (tren), salicylaldehyde, 5-chlorosalicylaldehyde, 5-bromosalicylaldehyde, and potassium borohydride were obtained from Aldrich. Hydrated Ga and In salts were obtained from Alfa. All chemicals were used without further purification.

Instrumentation. NMR spectra were recorded on Bruker AC-200E (¹H, ¹³C, ¹H—¹H COSY, ¹³C APT NMR), Varian XL 300 (¹H, VT NMR), and Bruker WH-400 (¹H NMR) spectrometers and are reported as δ in ppm from TMS. Mass spectra (Cs⁺ LSIMS) were obtained on a Kratos Concept II H32Q instrument with 3-nitrobenzyl alcohol or thioglycerol as the matrix. Infrared spectra were recorded as KBr disks on a Perkin-Elmer PE 783 spectrophotometer in the range 4000–400 cm⁻¹ and were referenced to polystyrene film (data are found in Table 1). Melting points were measured on a Mel-Temp apparatus and are uncorrected. C, H, N analyses were performed by Mr. Peter Borda of UBC. Conductance measurements were made with a Yellow Springs YS-1 Model 35 conductance meter using a solute concentration of 10⁻³ M at 25 °C.

1,10-Bis(2-hydroxybenzyl)-1,4,7,10-tetraazadecane (H₂bad). To a hot solution of triethylenetetramine (2 g, 0.014 mol) in ethanol (200 mL) was added a hot solution of salicylaldehyde (3.67 g, 0.030 mol) in ethanol (200 mL). While the solution was still hot, KBH₄ (1.66 g, 0.031 mol) was added in small quantities over 10 min. The solution was heated (approximately 50 °C) and stirred for an additional 2 h. The solvent was removed under reduced pressure, leaving a white residue. NH₄OAc (3 g) in 50 mL water was added to the white residue. The aqueous mixture was then extracted with chloroform (3 × 100 mL). The organic fractions were combined, washed with distilled water (3 × 100 mL), and then dried over anhydrous MgSO₄. The solution was filtered and the chloroform removed on a rotary evaporator to give a yellow oil. The oil was dried in vacuo at 60 °C for 24 h, yielding 12 g (84%). Elemental analysis of the yellow oil was not possible. LSIMS: *m/z* = 359 ([M + 1]⁺, [C₂₆H₃₁N₄O₂]⁺), *m/z* = 253 ([C₁₃H₂₅N₄O]⁺). ¹H and ¹³C NMR spectral data are listed in Tables 2 and 3, respectively.

Reaction of H₂bad with Acetone (H₂badAc). H₂bad (3 g, 8.4 mol) was dissolved in acetone (50 mL), and the solution was refluxed for 3 h. A white precipitate formed as the solution cooled to room temperature. Characterization of the precipitate revealed it to be the amine phenol with two 2-propylene groups, one bridging the first and second and one bridging the third and fourth N atoms, thereby forming two five-membered imidazolidine rings with the tren backbone (Scheme 1). Yield: 1.95 g (53%). Mp: 167–8 °C Anal. Calcd (found) for C₂₆H₃₈N₄O₂: C, 71.20 (70.90); H, 8.73 (8.83); N, 12.77 (12.70). LSIMS: *m/z* = 439 ([M + 1]⁺, [C₂₆H₃₉N₄O₂]⁺), *m/z* = 399 ([C₂₃H₃₅N₄O₂]⁺). ¹H NMR and infrared spectral data are listed in Table 4 and 1, respectively.

1,10-Bis(2-hydroxy-5-chlorobenzyl)-1,4,7,10-tetraazadecane (H₂Clbad). The preparation of 1,10-bis(2-hydroxy-5-chlorobenzyl)-1,4,7,10-tetraazadecane (H₂Clbad) was similar to the procedure for the preparation of H₂bad. The synthesis employed triethylenetetramine (2 g, 0.014 mol), 5-chlorosalicylaldehyde (4.70 g, 0.030 mol), and KBH₄ (1.66 g, 0.031 mol) and yielded 4.62 g (79%). Elemental analysis of the resulting oil was not possible. LSIMS: *m/z* = 427 ([M + 1]⁺

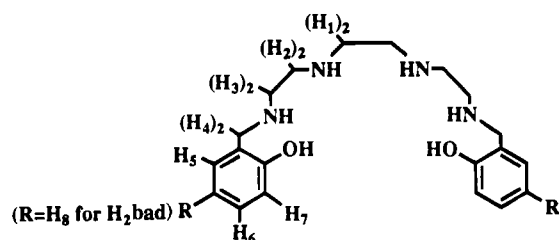
(14) Evans, D. F.; Jakubovic, D. A. *J. Chem. Soc., Dalton Trans.* **1988**, 2927.

(15) Evans, D. F.; Jakubovic, D. A. *Polyhedron* **1988**, 7, 1881.

(16) Tsang, B. W.; Mathias, C. J.; Green, M. A. *J. Nucl. Med.* **1993**, 34, 1127.

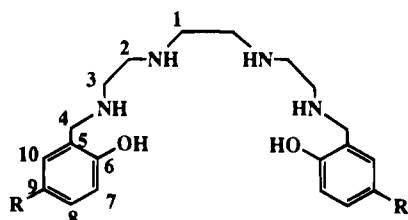
Table 1. IR Spectral Data (cm⁻¹, KBr disk) for the Acetone Adducts of the Trien-Based Amine Phenols and for the Ga and In Complexes of the Trien-Based N₄O₂ Amine Phenols

compound	ν_{OH} and/or ν_{NH}	ν_{CH}	δ_{NH}	$\nu_{\text{C}=\text{C}}$
H ₂ badAc	3600–3300 b, w	3000–2600 s	1610 m; 1590 m	1500–1460 s
H ₂ ClbadAc	3600–3300 b, w	3000–2600 s	1610 m; 1585 m	1500–1440 s
H ₂ BrbadAc	3620–3300 b, w	3000–2600 s	1605 m; 1580 m	1500–1440 s
[Ga(Clbad)]ClO ₄ ·H ₂ O	3640–3340 b, m; 3300 m; 3250 m	2980–2860 m	1595 m; 1555 w	1500–1410 s
[Ga(Brbad)]ClO ₄ ·H ₂ O	3640–3340 b, m; 3290 m; 3240 m	2980–2860 m	1590 m; 1555 w	1500–1410 s
[In(bad)]I·H ₂ O	3660–3300 b, s; 3230 s; 3100 s	2980–2860 s	1595 s; 1568 m	1480–1430 s
[In(Clbad)]ClO ₄	3640–3340 b, m; 3250 m; 3200 m	2980–2860 m	1590 m; 1560 w	1500–1400 s
[In(Brbad)]Cl·2H ₂ O	3660–3300 b, s; 3240 s; 3100 s	2980–2860 s	1590 s; 1555 m	1480–1400 s

Table 2. ¹H NMR Data (300 MHz, CDCl₃) for the Trien-Based N₄O₂ Amine Phenols

assignt	H ₂ bad (R = H)	H ₂ Clbad (R = Cl)	H ₂ Brbad (R = Br)
H ₁ /H ₂ /H ₃	2.74 (m, 12H) ^a	2.72 (m, 12H) ^a	2.74 (m, 12H) ^a
H ₄	3.93 (s, 4H)	3.90 (s, 4H)	3.93 (s, 4H)
H ₅	6.95 (dd, 2H)	6.92 (d, 2H)	7.08 (d, 2H)
H ₆	7.11 (td, 2H)	7.06 (dd, 2H)	7.22 (dd, 2H)
H ₇	6.75 (m, 2H) ^b	6.68 (d, 2H)	6.67 (d, 2H)
H ₈	6.75 (m, 2H) ^b		
NH	5.20 (b, s)	5.35 (b, s)	5.30 (b, s)

^a Signal consists of overlapping multiplets attributed to the 12 hydrogens of H₁, H₂, and H₃. ^b Multiplet at 6.75ppm is attributed to the 4 hydrogens of H₇ and H₈.

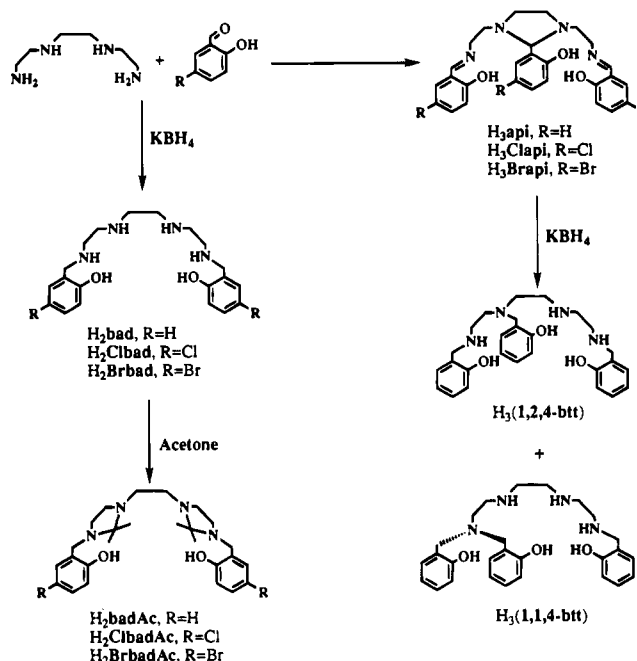
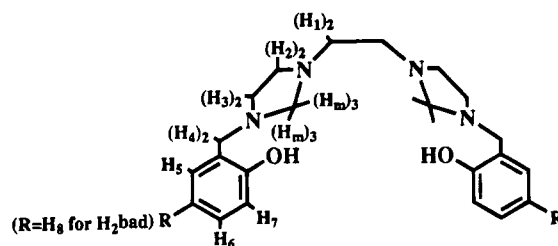
Table 3. ¹³C NMR Data (200 MHz, CDCl₃) for the Trien-Based N₄O₂ Amine Phenols

assignt	H ₂ bad (R = H)	H ₂ Clbad (R = Cl)	H ₂ Brbad (R = Br)
C ₁ , C ₂ , C ₃	48.0, 48.5, 49.1	48.0, 48.3, 49.0	48.1, 48.4, 49.1
C ₄	52.4	51.9	51.9
C ₅	122.7	123.4	124.6
C ₆	158.3	156.9	157.5
C ₇	116.3	117.6	118.2
C ₈	128.6	128.4	130.9
C ₉	118.9	124.1	110.6
C ₁₀	128.4	128.0	131.3

[C₂₀H₂₉Cl₂N₄O₂]⁺, *m/z* = 287 ([C₁₃H₂₄Cl₁N₄O₁]⁺). ¹H and ¹³C NMR spectral data are listed in Tables 2 and 3, respectively.

Reaction of H₂Clbad with Acetone (H₂ClbadAc). The reaction of H₂Clbad (3 g, 7.0 mmol) with acetone (50 mL) was similar to the reaction of H₂bad with acetone. The yield was 2.21 g (62%). Mp: 168–9 °C. Anal. Calcd (found) for C₂₆H₃₆Cl₂N₄O₂: C, 61.52 (61.32); H, 7.15 (7.07); N, 11.04 (11.10). LSIMS: *m/z* = 507 ([M + 1]⁺, [C₂₆H₃₇Cl₂N₄O₂]⁺), *m/z* = 467 ([C₂₃H₃₃Cl₂N₄O₂]⁺). ¹H NMR and infrared spectral data are listed in Tables 4 and 1, respectively.

1,10-Bis(2-hydroxy-5-bromobenzyl)-1,4,7,10-tetraazadecane (H₂Brbad). The preparation of 1,10-bis(2-hydroxy-5-bromobenzyl)-1,4,7,10-tetraazadecane (H₂Brbad) was similar to the procedure for the preparation of H₂bad and employed triethylenetetramine (2 g, 0.014 mol), 5-bromosalicylaldehyde (6.03 g, 0.030 mol), and KBH₄ (1.66 g, 0.031 mol). The yield was 5.51 g (78%). Elemental analysis of the

Scheme 1**Table 4.** ¹H NMR Data (300 MHz, CDCl₃) for the Acetone Adducts of the Trien-Based N₄O₂ Amine Phenols

assignt	H ₂ badAc (R = H)	H ₂ ClbadAc (R = Cl)	H ₂ BrbadAc (R = Br)
H ₁	2.60 (s, 4H)	2.58 (s, 4H)	2.58 (s, 4H)
H ₂ /H ₃	2.86 (m, 8H) ^a	2.86 (m, 8H) ^a	2.86 (m, 8H) ^a
H ₄	3.82 (s, 4H)	3.77 (s, 4H)	3.78 (s, 4H)
H ₅	6.90 (dd, 2H)	6.97 (d, 2H)	7.05 (d, 2H)
H ₆	7.16 (td, 2H)	7.11 (dd, 2H)	7.24 (dd, 2H)
H ₇	6.78 (m, 2H) ^b	6.73 (d, 2H)	6.68 (d, 2H)
H ₈	6.78 (m, 2H) ^b		
H _m	1.16 (s, 12H)	1.15 (s, 12H)	1.14 (s, 12H)

^a Signal consists of overlapping multiplets attributed to the 8 hydrogens of H₂ and H₃. ^b Multiplet at 6.78 ppm is attributed to the 4 hydrogens of H₇ and H₈.

resulting oil was not possible. LSIMS: *m/z* = 517 ([M + 1]⁺, [C₂₀H₂₉Br₂N₄O₂]⁺). ¹H and ¹³C NMR spectral data are listed in Tables 2 and 3, respectively.

Reaction of H₂Brbad with Acetone (H₂BrbadAc). The reaction of H₂Brbad (3 g, 5.8 mmol) with acetone (50 mL) was similar to the reaction of H₂bad with acetone. The yield was 1.94 g (56%). Mp: 165–6 °C. Anal. Calcd (found) for C₂₆H₃₆Br₂N₄O₂: C, 52.36 (52.22);

Table 5. Analytical [Calcd (Found)], LSIMS Mass Spectral,^a and Conductance ($\Omega^{-1} \text{ mol}^{-1} \text{ cm}^2$) Data for the Ga and In Complexes of the Trien-Based N_4O_2 Amine Phenols

complex	% C	% H	% N	<i>m/z</i>	molar conductance
[Ga(Clbad)]ClO ₄ ·H ₂ O	39.22 (38.98)	4.61 (4.49)	9.15 (9.11)	495 [ML] ⁺ , 594 [(ML)(A)] ⁺ , 1089 [2(ML)(A)] ⁺	120
[Ga(Brbad)]ClO ₄ ·H ₂ O	34.25 (34.01)	4.02 (3.98)	7.99 (7.86)	583 [ML] ⁺ , 684 [(ML)(A)] ⁺ , 1267 [2(ML)(A)] ⁺	122
[In(bad)]I·H ₂ O	38.98 (38.76)	4.91 (4.86)	9.09 (9.02)	471 [ML] ⁺ , 599 [(HML)(A)] ⁺	124
[In(Clbad)]ClO ₄	37.56 (37.88)	4.10 (4.30)	8.76 (8.59)	539 [ML] ⁺	123
[In(Brbad)]Cl·2H ₂ O	34.29 (34.42)	4.32 (3.96)	8.00 (8.29)	629 [ML] ⁺ , 665 [(HML)(A)] ⁺ , 1293 [2(ML)(A)] ⁺	120

^a ML indicates metal ion-containing cation; A indicates anion.

Table 6. ¹H NMR Data (400 MHz, DMSO-*d*₆) for the Ga and In Trien-Based N_4O_2 Amine Phenol Complexes

complex	aromatic hydrogens	benzylic hydrogens, hydrogens on trien backbone, and hydrogens on coordinated N atoms
[Ga(Clbad)]ClO ₄ ·H ₂ O	6.44 (d, 1H), 6.56 (d, 1H), 7.04 (m, 4H)	5.70 (m, 1H), 4.95 (m, 1H), 4.85 (m, 1H), 4.44 (m, 1H), 4.26 (m, 1H), 4.00 (t, 1H), 3.72 (m, 1H), 3.58 (d, 1H), 3.20–2.40 (m, 12H)
[Ga(Brbad)]ClO ₄ ·H ₂ O	6.44 (d, 1H), 6.56 (d, 1H), 7.18 (m, 4H)	5.44 (m, 1H), 4.96 (m, 1H), 4.88 (m, 1H), 4.50 (m, 1H), 4.30 (m, 1H), 4.04 (t, 1H), 3.76 (m, 1H), 3.60 (d, 1H), 3.28–2.40 (m, 12H)
[In(bad)]I·H ₂ O	6.48 (m, 3H), 6.64 (t, 2H), 7.04 (m, 3H)	5.14 (m, 1H), 4.98 (t, 1H), 4.86 (m, 1H), 4.70 (m, 1H), 4.56 (m, 2H), 4.24 (t, 1H), 4.14 (t, 1H), 3.72 (m, 1H), 3.20–2.40 (m, 12H)
[In(Clbad)]ClO ₄	6.46 (d, 1H), 6.60 (d, 1H), 7.10 (m, 4H)	5.00–4.95 (m, 2H), 4.78 (m, 1H), 4.58 (m, 1H), 4.44 (m, 2H), 4.14 (t, 1H), 4.02 (t, 1H), 3.70 (dd, 1H), 3.52 (dd, 1H), 3.10–2.40 (m, 10H)
[In(Brbad)]Cl·2H ₂ O	6.42 (d, 1H), 6.56 (d, 1H), 7.10 (m, 4H)	5.44 (m, 1H), 4.96 (m, 1H), 4.88 (m, 1H), 4.50 (m, 1H), 4.30 (m, 1H), 4.04 (t, 1H), 3.76 (m, 1H), 3.60 (d, 1H), 3.28–2.45 (m, 12H)

H, 6.08 (6.00) N, 9.39 (9.41). LSIMS: *m/z* = 597 ([M + 1]⁺, [C₂₆H₃₇Br₂N₄O₂]⁺), *m/z* = 557 ([C₂₃H₃₃Br₂N₄O₂]⁺). ¹H NMR and infrared spectral data are listed in Tables 4 and 1, respectively.

Synthesis of Metal Complexes. As many of the syntheses were similar, detailed procedures are only given for representative examples. All the Ga and In complexes that were prepared, along with their analytical and mass spectral data, are listed in Table 5, while infrared data are given in Table 1. Molar conductance measurements of the metal complexes (10^{-3} M in acetonitrile, 25 °C) are also given in Table 5. ¹H NMR spectra of all metal complexes were recorded in DMSO-*d*₆; rough assignments of the observed ¹H resonance signals are listed in Table 6. The syntheses of the Ga and In complexes gave yields of 72–77%. The synthesis of the Ga and In complexes described below employed the perchlorate salts of the respective metal ions and the trien-based amine phenols (**H₂bad**, **H₂Clbad**, **H₂Brbad**); however, Ga and In complexes can also be prepared from other Ga or In salts and/or with the acetone adducts **H₂badAc**, **H₂ClbadAc**, and **H₂BrbadAc**. Upon complexation, the imidazolidine rings open, thereby freeing the amine nitrogens for coordination to the metal ion.

N.B. Perchlorate salts of metal complexes are potentially explosive and should be handled with care.

[Ga(Brbad**)]ClO₄·H₂O.** To a solution of Ga(ClO₄)₃·6H₂O (405 mg, 0.85 mmol) and **H₂Brbad** (719 mg, 1.4 mmol) in methanol (15 mL) was added NaOAc (245 mg, 3.0 mmol) in methanol (5 mL). The mixture was immediately filtered, and the filtrate was left at room temperature. Slow evaporation of the solvent yielded a beige precipitate, which was collected by filtration and washed with cold methanol, followed by diethyl ether. The precipitate was dried *in vacuo* at 80 °C to yield 441 mg (74%). Recrystallization of the precipitate from methanol and/or DMSO afforded crystals suitable for X-ray crystallographic analysis.

[In(Clbad**)]ClO₄.** To a solution of In(ClO₄)₃·8H₂O (503 mg, 0.90 mmol) and **H₂Clbad** (651 mg, 1.5 mmol) in methanol (15 mL) was added NaOAc (245 mg, 3.0 mmol) in methanol (5 mL). The mixture was immediately filtered, and the filtrate was left to stand at room temperature. Slow evaporation of the solvent yielded a white precipitate, which was collected by filtration and washed with cold methanol, followed by diethyl ether. The precipitate was dried *in vacuo* at 80 °C to yield 444 mg (77%).

X-ray Crystallographic Determination of [Ga(Brbad**)]ClO₄·DMSO.** Colorless, block-shaped crystals of [Ga(**Brbad**)]ClO₄·DMSO were grown from a methanol/DMSO solution by slow evaporation of the solvents at room temperature. A suitable specimen was mounted on a glass fiber and placed on an Enraf-Nonius CAD-4 diffractometer at room temperature. A preliminary orthorhombic unit cell was established by a three-dimensional search in reciprocal space. Final lattice

parameters were obtained by least-squares refinement of the angular settings of 25 reflections distributed throughout reciprocal space in the 2θ range $23.4^\circ \leq 2\theta \leq 27.9^\circ$. All data *h,k,l* were collected at 20(2) °C in the 2θ range $2.0^\circ \leq 2\theta \leq 50.0^\circ$. Orientation and intensity control reflections were monitored every 200 reflections and every 2 h of data collection, respectively. Azimuthal (ψ) scans were recorded at the end of the data collection for three reflections near $\psi = 90^\circ$ at 10° increments of rotation of the crystal about the diffraction vector. Crystal data together with additional details about the diffraction experiment are listed in Table 7. The raw intensity data were converted into structure factor amplitudes (and their esd's) by correcting for scan speed, background, Lorentz, and polarization effects.¹⁷ No decay correction (maximum fluctuation of 1.9% over 55 h of X-ray exposure time) was applied, but the data were empirically corrected for absorption by means of the three ψ scans. Systematically absent reflections uniquely defined the space group to be *Pbca* (No. 61); these data were removed.

The structure was solved by standard Patterson methods¹⁸ with *Z* = 8 (from density calculations). The asymmetric unit contains one [Ga(**Brbad**)] cation together with a perchlorate anion and a DMSO molecule. The DMSO molecule is hydrogen bonded to a hydrogen of a secondary amine of the ligand backbone. Three of the four perchlorate oxygens suffer a 2-fold disorder around the pseudo-3-fold axis defined by the remaining Cl–O vector. They were assigned site occupancy factors of 0.5. The positional parameters of all non-hydrogen atoms in the asymmetric unit which are not disordered were refined with isotropic and later with anisotropic thermal parameters.¹⁸ A difference Fourier map calculated at this stage revealed the positional parameters of some hydrogen atoms; however, these atoms were added to the structure model at calculated positions [*d*(C–H) = 0.95 Å]¹⁹ with their thermal parameters tied to a free variable which refined in the least-squares procedure to a value of *U*(iso) = 0.048 Å. No shifts were detected in the final cycle of least-squares refinement. Neutral atomic scattering factors were used and corrections for anomalous dispersion were applied.²⁰ Final positional parameters and selected bond parameters for [Ga(**Brbad**)]ClO₄·DMSO are listed in Tables 8 and 9, respectively. A plot of the cation and the DMSO molecule in the asymmetric unit is presented in Figure 1. An ORTEP diagram of the disordered perchlorate anion as well as complete tables of distances,

(17) *MolEN Structure Determination Package*; Enraf-Nonius: Delft, The Netherlands, 1991.

(18) Sheldrick, G. M. *SHELX-76: Program for Crystal Structure Solution*; University of Cambridge: Cambridge, UK, 1976.

(19) Churchill, M. R. *Inorg. Chem.* **1973**, *12*, 1231.

(20) Cromer, D. T.; Waber, J. B. *International Tables for X-Ray Crystallography*; Kynoch Press: Birmingham, UK, 1974; Vol. IV, Tables 2.2B and 2.3.1.

Table 7. Summary of Crystallographic Data and Parameters for [Ga(Brbad)]ClO₄·DMSO

crystal size, mm ³	0.45 × 0.22 × 0.20
formula	C ₂₂ H ₃₂ Br ₂ ClGaN ₄ O ₇ S
fw	761.6
crystal syst	orthorhombic
space group	<i>Pbca</i> (No. 61)
<i>a</i> , Å	14.777(4)
<i>b</i> , Å	22.221(5)
<i>c</i> , Å	17.410(7)
<i>V</i> , Å ³	5717(5)
<i>Z</i>	8
ρ_c , g/cm ³	1.770
ρ_o , g/cm ³	1.78
μ (Mo K α), cm ⁻¹	39.4
radiation (λ , Å)	Mo K α (0.710 73)
monochromator	graphite crystal (2 θ_m = 12.2°)
diffractometer	Enraf-Nonius CAD-4
<i>T</i> , °C	20(2)
2 θ range, deg	2 ≤ 2 θ ≤ 30
reflections measd	0 ≤ <i>h</i> ≤ 17 0 ≤ <i>k</i> ≤ 26 0 ≤ <i>l</i> ≤ 20
scan mode	ω -2 θ
scan speed	variable
θ , deg/min (min/max)	1.7/5.5
scan width $\Delta\theta$, deg	0.80 + 0.35[tan(θ)]
abs cor	three ψ scans
transm factors	0.63–1.00
total data collected	5580
no. of unique data	5026
no. of obsd data [$F_o^2 \geq 3\sigma(F_o^2)$]	2230
<i>R</i> , % ^a	4.81
<i>R_w</i> , % ^a	5.22
no. of variables	341
max res electr dens	0.95

^a Definition of residuals and refinement parameters: $R = \sum ||F_o| - |F_c|| / \sum |F_o|$, $R_w = [\sum w||F_o| - |F_c||^2 / \sum w|F_o|^2]^{1/2}$, $w = 1/[\sigma^2(F)] + 0.0011F^2$.

angles, hydrogen atom parameters, and anisotropic thermal parameters are available as supplementary material.

Results and Discussion

Trien-Based N₄O₂ Amine Phenols. In previous studies, tripodal N₄O₃ and N₃O₃ amine phenols were prepared by reducing their Schiff base analogues with KBH₄.^{8–13} The Schiff base compounds were prepared from condensation reactions of the appropriate tripodal amine backbone with salicylaldehyde or ring-substituted salicylaldehyde. However, this method was not suitable for the preparation of the linear trien-based amine phenols H₂bad, H₂Clbad, and H₂Brbad. Reaction of salicylaldehyde or a substituted salicylaldehyde with trien resulted in the production of 2-(2-hydroxyphenyl)-1,3-bis[4-(2-hydroxyphenyl)-3-azaprop-4-en-1-yl]-1,3-imidazolidine (H₃api) or its ring-substituted analogues (H₃Clapi and H₃Brapi) (Scheme 1). Regardless of the ratio of aldehyde to amine, the resulting Schiff base incorporated an imidazolidine ring, which was formed by the reaction of a third aldehyde with the two inner adjacent secondary amine nitrogens of trien. This observation is consistent with the results found by other workers.^{14,21–24} Reduction of H₃api, H₃Clapi, or H₃Brapi with KBH₄ resulted in two isomeric products, *N,N',N''*-tris(2-hydroxybenzyl)triethylenetetramine (1,2,4-H₃btt), and *N,N',N''*-tris(2-hydroxybenzyl)triethylenetetramine (1,1,4-H₃btt) (Scheme 1). X-ray

Table 8. Positional Parameters and Isotropic Equivalent Thermal Parameters for Non-Hydrogen Atoms in [Ga(Brbad)]ClO₄·DMSO

atom	<i>x</i>	<i>y</i>	<i>z</i>	<i>B_{eq}</i> , Å ²
Br1	0.21693(9)	−0.00727(5)	0.07218(8)	6.04
Br2	0.32013(9)	−0.49413(6)	−0.15653(7)	4.05
Ga	0.55446(7)	−0.24658(5)	0.03114(6)	2.89
Cl	0.1715(2)	0.1378(1)	0.2351(2)	4.73
S	0.5724(2)	−0.0309(2)	0.1526(2)	5.08
O1	0.4296(4)	−0.2371(3)	0.0572(4)	3.07
O2	0.5483(5)	−0.2812(3)	−0.0694(4)	3.22
O3	0.1304(6)	0.1185(5)	0.1658(6)	6.62
O4A	0.1901(16)	0.1980(11)	0.2294(12)	8.26
O5A	0.2584(14)	0.1094(9)	0.2329(12)	7.49
O6A	0.1154(18)	0.1121(11)	0.2859(14)	9.86
O4B	0.2645(17)	0.1559(12)	0.2172(13)	9.64
O5B	0.1821(15)	0.1017(9)	0.3016(12)	7.51
O6B	0.1369(11)	0.1973(7)	0.2625(9)	5.12
O7	0.5698(6)	−0.0954(3)	0.1260(5)	5.33
N1	0.5571(5)	−0.1603(3)	−0.0139(4)	3.15
N2	0.6971(5)	−0.2404(4)	0.0123(4)	3.67
N3	0.5989(6)	−0.2249(4)	0.1457(4)	3.28
N4	0.5349(5)	−0.3313(3)	0.0799(4)	2.92
C1	0.3836(6)	−0.1866(5)	0.0572(5)	2.58
C2	0.3141(7)	−0.1793(5)	0.1135(6)	3.75
C3	0.2630(7)	−0.1260(5)	0.1159(6)	2.82
C4	0.2785(7)	−0.0817(5)	0.0644(6)	3.48
C5	0.3441(7)	−0.0888(5)	0.0088(6)	4.07
C6	0.3959(7)	−0.1397(4)	0.0058(5)	2.67
C7	0.4711(7)	−0.1475(5)	0.0542(5)	3.91
C8	0.6352(7)	−0.1578(5)	−0.0666(6)	4.70
C9	0.7176(7)	−0.1812(5)	−0.0227(6)	4.10
C10	0.7464(7)	−0.2502(5)	0.0855(6)	3.92
C11	0.6988(6)	−0.2146(5)	0.1488(6)	2.99
C12	0.5687(7)	−0.2759(5)	0.1953(6)	3.67
C13	0.5793(7)	−0.3354(4)	0.1566(6)	3.63
C14	0.5554(7)	−0.3826(4)	0.0310(6)	3.50
C15	0.4960(6)	−0.3807(4)	−0.0409(5)	2.55
C16	0.4408(7)	−0.4276(4)	−0.0615(6)	3.34
C17	0.3917(6)	−0.4260(4)	−0.1279(6)	2.61
C18	0.3934(7)	−0.3762(5)	−0.1738(6)	3.33
C19	0.4438(7)	−0.3271(4)	−0.1538(5)	3.10
C20	0.4971(7)	−0.3283(4)	−0.0870(6)	2.68
C21	0.5948(9)	−0.0353(6)	0.2525(6)	5.08
C22	0.4686(10)	−0.0186(10)	0.1643(8)	11.07

^a Disordered O atoms (O4A to O6B) were refined with isotropic thermal parameters. The thermal parameter given for anisotropically refined atoms is the isotropic equivalent thermal parameter defined as $B_{eq} = \frac{1}{3}\pi^2[\sum_i \sum_j U_{ij} a_i^* a_j^* a_i a_j]$.

structures of Yb(1,2,4-btt) and In(1,1,4-btt) have been communicated.²⁴

Preparation of the desired linear N₄O₂ amine phenols (H₂bad, H₂Clbad, H₂Brbad) involved a modified amine phenol synthesis. Instead of performing the KBH₄ reduction on the isolated Schiff base compound, the modified synthesis involved the direct addition of KBH₄ to hot methanolic solutions of triethylenetetramine and salicylaldehyde or substituted salicylaldehyde. No uncomplexed Schiff bases were ever isolated. The oily products of the *in situ* reduction were characterized as the desired N₄O₂ amine phenols; however reaction of the amine phenols with acetone resulted in the formation of the easily characterizable and much more tractable acetone adducts with two imidazolidine rings (Scheme 1). The imidazolidine rings have also been observed in the acetone adducts of the tap-based amine phenols **III**¹⁰ but no adducts were produced for tren-based **I**⁸ or tame-based **II**⁹ amine phenols, the parent amines lacking the required HNCH₂CH₂NH functionality to form imidazolidine rings. All the trien-based amine phenols (H₂bad, H₂Clbad, H₂Brbad) and their acetone adducts (H₂badAc, H₂ClbadAc, H₂BrbadAc) were characterized by a variety of spectroscopic techniques (IR, NMR, and LSIMS) and elemental analyses. These amine phenols and their adducts were soluble in polar solvents such

(21) Das Sarma, B.; Bailar, J. C., Jr. *J. Am. Chem. Soc.* **1954**, *76*, 4051.

(22) Das Sarma, B.; Bailar, J. C., Jr. *J. Am. Chem. Soc.* **1955**, *77*, 5476.

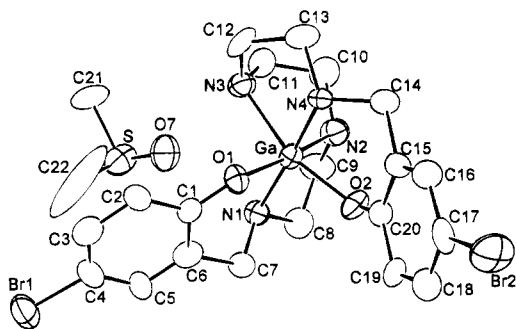
(23) Das Sarma, B.; Ray, K. R.; Sievers, R. E.; Bailar, J. C., Jr. *J. Am. Chem. Soc.* **1964**, *86*, 14.

(24) Yang, L.-W.; Liu, S.; Wong, E.; Rettig, S. J.; Orvig, C. Submitted for publication.

Table 9. Selected Bond Distances (Å) and Angles (deg) for the [Ga(Brbad)]⁺ Cation in [Ga(Brbad)]ClO₄·DMSO

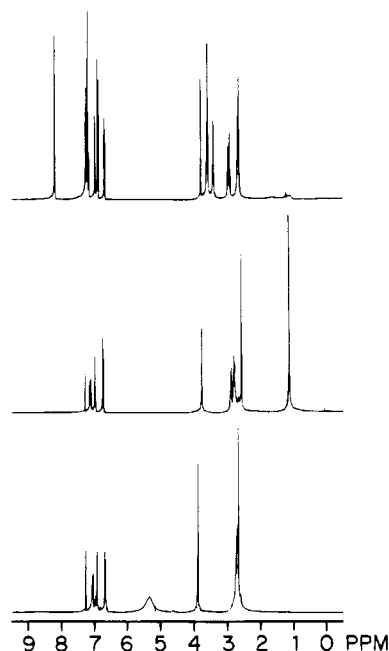
Ga—O1	1.911(6)	O1—Ga—O2	102.4(3)
Ga—O2	1.914(6)	O1—Ga—N1	90.4(3)
Ga—N1	2.073(7)	O1—Ga—N2	168.8(3)
Ga—N2	2.138(8)	O1—Ga—N3	92.9(3)
Ga—N3	2.153(8)	O1—Ga—N4	82.5(3)
Ga—N4	2.085(7)	O2—Ga—N1	91.5(3)
Br1—C4	1.892(10)	O2—Ga—N2	86.1(3)
Br2—C17	1.913(9)	O2—Ga—N3	162.0(3)
O1—C1	1.313(10)	O2—Ga—N4	90.1(3)
O2—C20	1.327(11)	N1—Ga—N2	82.2(3)
N1—C7	1.479(12)	N1—Ga—N3	97.9(3)
N1—C8	1.476(12)	N1—Ga—N4	172.8(3)
N2—C9	1.481(13)	N2—Ga—N3	80.1(3)
N2—C10	1.484(13)	N2—Ga—N4	104.9(3)
N3—C11	1.496(12)	N3—Ga—N4	82.4(3)
N3—C12	1.493(13)	Ga—O1—C1	126.5(6)
N4—C13	1.490(12)	Ga—O2—C20	123.7(6)
N4—C14	1.454(11)	Ga—N1—C7	109.9(6)
C1—C2	1.429(13)	Ga—N1—C8	106.6(6)
C1—C6	1.386(13)	C7—N1—C8	111.7(7)
C2—C3	1.407(13)	Ga—N2—C9	108.8(6)
C3—C4	1.351(14)	Ga—N2—C10	110.0(6)
C4—C5	1.380(14)	C9—N2—C10	112.6(8)
C5—C6	1.367(13)	Ga—N3—C11	111.7(6)
C6—C7	1.535(13)	Ga—N3—C12	106.0(6)
C8—C9	1.529(15)	C11—N3—C12	112.9(8)
C10—C11	1.529(13)	Ga—N4—C13	111.0(6)
C12—C13	1.493(14)	Ga—N4—C14	116.2(6)
C14—C15	1.531(13)	C13—N4—C14	112.6(7)
C15—C16	1.371(13)		
C15—C20	1.412(13)		
C16—C17	1.364(13)		
C17—C18	1.365(14)		
C18—C19	1.366(13)		
C19—C20	1.406(13)		
O7···N1 ^a	2.836		

^a O7 is probably hydrogen bonded to the amine hydrogen atom on N1; however, this hydrogen position was not located in the least-squares calculations.

**Figure 1.** ORTEP drawing of the [Ga(Brbad)]⁺ cation and DMSO solvate in [Ga(Brbad)]ClO₄·DMSO showing the crystallographic numbering scheme.

as methanol and chloroform, and unlike Schiff bases, they were hydrolytically stable under both acidic and basic conditions. Further mechanistic implications on the imidazolidine ring formation and opening reactions have been discussed already.²⁴ The trien-based amine phenols were also water soluble at low pH in millimolar concentration.

¹H NMR spectral data for trien-based amine phenols (H₂bad, H₂Clbad, H₂Brbad) are summarized in Table 2, and these showed the amine phenols to be symmetric about the central ethylene moiety. This was confirmed in the ¹³C NMR spectra (Table 3) where only 10 out of a possible 20 ¹³C resonance signals were observed. ¹H NMR spectra of H₃Clapi, H₂Clbad, and H₂ClbadAc are given in Figure 2. The two hydroxybenzyl groups attached to the trien backbone via the terminal amine nitrogens were chemically equivalent because only a single set

**Figure 2.** ¹H NMR spectra (300 MHz, CDCl₃) of H₃Clapi (top), H₂ClbadAc (middle), and H₂Clbad (bottom).

of ¹H resonance signals was observed in the aromatic region of the spectra (6.5–7.5 ppm) (Figure 2, spectrum of H₂Clbad). This set of ¹H resonance signals corresponded to the hydrogen atoms on two chemically equivalent hydroxybenzyl groups. The presence of a third group, either bridging two amine nitrogens to form an imidazolidine ring^{21–24} (as in H₃Clapi; Figure 2) or simply attached to one amine nitrogen (as in the isomers 1,1,4-H₃btt and 1,2,4-H₃btt),²⁴ would result in a second set of aromatic resonance signals. Additional evidence confirming the absence of a third hydroxybenzyl group was that only one singlet was observed for the benzylic hydrogens in the ¹H NMR spectra. This singlet at ~3.9 ppm corresponding to the benzylic hydrogens also confirmed the successful synthesis of the amine phenols. No unreduced Schiff base was present in the oily product as no imine H singlet was observed ~8.3 ppm.

The hydrogens on the trien backbone appeared as a complex set of overlapping resonance signals from 2.60 to 2.75 ppm (Figure 2, spectra of H₃Clbad and H₃ClbadAc). Specific assignments of these resonance signals were not possible; however, integration of the overlapping multiplet, of the signals in the aromatic region, and of the singlet from the benzylic hydrogens confirmed the formulation of N₄O₂ amine phenols with two hydroxybenzyl groups attached to the ends of the trien backbone. Mass spectral data were also consistent with this formulation.

Acetone adducts of the linear trien-based N₄O₂ amine phenols (H₂badAc, H₂ClbadAc, H₂BrbadAc) were prepared by refluxing the amine phenols in acetone. Each adduct contained two imidazolidine rings, which were formed by the reaction of acetone with an inner amine nitrogen and a terminal amine nitrogen (Scheme 1). Elemental analyses and spectroscopic studies were consistent with the proposed formulations. ¹H NMR spectra of the adducts were similar to the spectra of the corresponding amine phenols with the exception of singlets at ~1.15 and at ~2.58 ppm. The singlet at 1.15 ppm corresponded to the 12 methyl hydrogens on the two imidazolidine rings. The singlet at 2.58 ppm was from the four methylene hydrogens (H_i) located between the two inner (now tertiary) amine nitrogen atoms of the trien backbone. In the ¹H NMR spectra of the amine phenols (H₂bad, H₂Clbad, H₂Brbad), this singlet

overlapped with resonance signals from hydrogens H₃ and H₄ on the outer ethylene groups lying between the inner amine nitrogen and the terminal amine nitrogen. The formation of two imidazolidine rings in the acetone adduct shifted the signals of H₃ and H₄ downfield from ~2.75 to ~2.86 ppm. The four H₁ hydrogens were shifted slightly upfield by the formation of the imidazolidine rings. Hence, it was possible to identify the singlet at 2.58 ppm as the four methylene hydrogens, H₁.

In the IR spectra of the acetone adducts, the absence of strong bands at 1620–1500 cm⁻¹ (characteristic of imine C=N bond stretches) confirmed the successful *in situ* reduction by KBH₄ of the Schiff bases. Instead, two medium bands at 1610–1580 cm⁻¹ were observed which were attributed to N–H bending modes. Broad bands in the region 3600–3300 cm⁻¹ suggested the possibility of intrastand hydrogen bonding, similar to those observed in the acetone adduct of the tap-based amine phenols.¹⁰ The IR spectra of the adducts (H₂badAc, H₂ClbadAc, H₂BrbadAc) were very similar to the spectra of the original amine phenols (H₂bad, H₂Clbad, H₂Brbad) with the exception that the spectra of the adducts showed more bands in the region 3000–2600 cm⁻¹ because of the four methyl groups. In addition, bands due to N–H bending modes are expected to show a bathochromic shift in going from the amine phenols to the acetone adducts.

Ga and In Complexes. Monocationic Ga and In complexes were easily prepared from reactions of the trien-based amine phenols (H₂bad, H₂Clbad, H₂Brbad) with hydrated metal salts in the presence of excess sodium acetate. Metal complexes could also be prepared from the reaction of metal salts with the acetone adducts of the amine phenols. During complexation of the metal ion, the two imidazolidine rings open, thereby freeing the amine nitrogens for coordination to the metal ion. The imidazolidine rings bring a degree of preorganization to the amine phenol ligands, as observed in the acetone adducts of the tap-based amine phenols III.¹⁰ In the complexation of the Schiff base, H₃api, and its ring-substituted analogues with metal ions such as Fe³⁺, Al³⁺, Ga³⁺, In³⁺, Mn³⁺, and Co³⁺, the imidazolidine ring opens and allows all four amine nitrogens to coordinate to the metal ion.^{21–27} Similar opening of the imidazolidine rings is also observed in the complexation of Ga³⁺ and In³⁺ with the acetone adduct of tap-based amine phenols.¹⁰ One exception among these metal ions is a dinuclear Fe complex with the phenolate oxygen atom of the middle hydroxybenzyl group bridging two Fe centers.²⁸

Ga and In complexes were found to be quite stable under both basic (no metal hydroxide forms in the presence of sodium hydroxide) and weakly acidic conditions (stable to the acetic acid formed when the metal ion coordinated with the amine phenol ligand in the presence of sodium acetate). The complexes were soluble in DMSO and slightly soluble in alcohols and in low pH aqueous solutions (pH ~2). All the metal complexes were characterized by spectroscopic techniques (IR, NMR, and LSIMS), molar conductivity measurements, and elemental analyses, and these data were consistent with the proposed formulation of monocationic, hexacoordinated complexes (Tables 1, 5, and 6). An X-ray crystallographic analysis of [Ga(Brbad)]ClO₄·DMSO was performed and found to be consistent with the proposed formulation (*vide infra*).

Attempts to isolate Al³⁺ complexes were unsuccessful, even

in the presence of excess ligand, as precipitation of aluminum hydroxide often interfered with, and accompanied, the isolation of the complexes. Al, Ga, and In complexes of the sulfonated N₄O₂ Schiff base analogs have been studied, and the pM value for the Al complex was 10 orders of magnitude less than that for the Ga complex.^{14,15} These complexes were prepared by a template reaction, in which the Schiff base was synthesized *in situ* from the sulfonated salicylaldehyde and triethylenetetramine in the presence of the metal ion; however, the actual complexes were not isolated. Clearly, the Al complex is much less stable than its Ga congener.

IR spectral data of the Ga and In complexes showed medium to strong bands in the region 3250–3100 cm⁻¹ and medium to weak bands in the 1595–1555 cm⁻¹ region, corresponding to N–H stretching and bending modes of the coordinated amines, respectively. Upon coordination of the amine phenols, there was a general bathochromic shift of ~20 cm⁻¹ in the N–H bending modes, which was consistent with observations in previous studies.^{8–12} Broad O–H stretching bands in the region 3640–3300 cm⁻¹ suggested, in most cases, the presence of hydrogen bonding between the metal complexes and water molecules. A comparison of the IR data of the amine phenol acetone adducts with those of the metal complexes revealed new bands which appeared below 600 cm⁻¹ in the spectra of the metal complexes. These additional bands are probably M–O or M–N stretches; however, assignments of these bands were not conclusive because of their low energies. For the perchlorate complexes, a strong broad perchlorate band was observed at 1100 cm⁻¹.

Molar conductivity measurements in acetonitrile of all the Ga and In complexes showed values (Table 5) of 120–124 Ω⁻¹ mol⁻¹ cm² (25 °C); this was consistent with a 1:1 electrolyte, i.e. a monocationic metal complex formulation.²⁹ In the LSIMS of the Ga and In complexes, the molecular ion [ML]⁺ peaks were detected as well as [HMLA]⁺ or [MLA]⁺ peaks where A is the anion present in the complex (Table 5). For some of the metal complexes, dinuclear [(ML)₂A]⁺ peaks were also seen; their presence was probably caused by dimerization in the mass spectrometer.

¹H NMR spectra of the metal complexes were recorded in DMSO-*d*₆ and were very similar to each other with the exception of the aromatic region (6.5–7.5 ppm). The spectra were extremely complex and detailed assignments of the individual resonances were not carried out, but tentative assignments are given in Table 6. In the free amine phenols, the two hydroxybenzyl groups attached to the terminal amine nitrogens were chemically equivalent in both the ¹H and ¹³C NMR spectra (Tables 2 and 3). Coordination of the amine phenols to the metal ions caused a greater complexity of the aromatic resonance signals; this was attributed to the two hydroxybenzyl groups becoming nonequivalent during complexation. In addition, the singlet from the benzylic hydrogens and the multiplet from the aliphatic hydrogens on the trien backbone became a complex series of overlapping signals from 2.3 to 5.0 ppm. These complex multiplets were observed as high as 120 °C (Figure 3). Nonequivalence of the hydroxybenzyl groups was also observed at elevated temperature. This clearly demonstrated the rigid intact structure of the Ga and In complexes in solution. NMR spectral data were consistent with the solid-state structure of [Ga(Brbad)]⁺. This was supported by the ¹³C NMR spectrum of [Ga(Clbad)]ClO₄ which showed 20 ¹³C resonance signals while the ¹³C NMR spectra of the free amine phenols showed only 10 ¹³C resonance signals.

As the NMR spectra of the Ga and In complexes were very

(25) Dodson, G. G.; Hall, D. *J. Inorg. Nucl. Chem.* **1961**, *23*, 33.

(26) Cradwick, P. D.; Cradwick, M. E.; Dodson, G. G.; Hall, D.; Waters, T. N. *Acta Crystallogr.* **1972**, *B28*, 45.

(27) Sinn, E.; Sim, G.; Dose, E. V.; Tweedle, M. F.; Wilson, L. J. *J. Am. Chem. Soc.* **1978**, *100*, 3375.

(28) Piovesana, C. O.; Tarantelli, T.; Zanazzi, P. F. *Inorg. Chem.* **1982**, *21*, 2444.

(29) Geary, W. J. *Coord. Chem. Rev.* **1971**, *7*, 81.

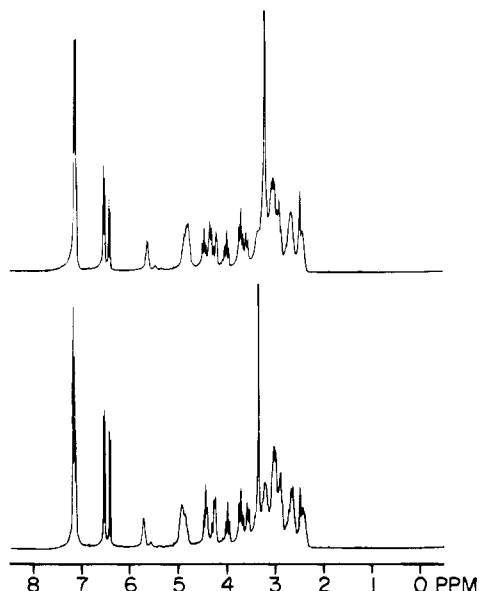
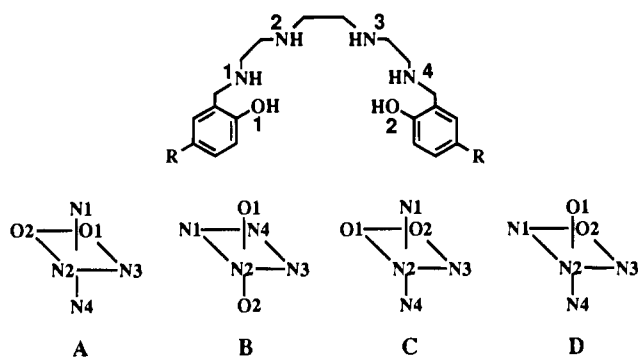


Figure 3. ^1H NMR spectra (300 MHz, $\text{DMSO}-d_6$) of $[\text{Ga}(\text{Brbad})]\text{ClO}_4$ at room temperature (bottom) and at 120 °C (top).

Chart 2



similar, variable-temperature ^1H NMR experiments were performed only for $[\text{Ga}(\text{Brbad})]\text{ClO}_4$ (Figure 3), $[\text{In}(\text{Brbad})]\text{Cl}$, and $[\text{In}(\text{bad})]\text{I}$. No significant change in the spectral data was observed for any of the metal complexes as the temperature was raised from room temperature to 120 °C. Minor shifts of hydrogen resonance signals and a slight broadening of the signals were observed (Figure 3). Thermal vibrations of the coordinated ligand at the elevated temperature explain the observed broadening and shift of the ^1H resonance signals.

X-ray Crystal Structure of $[\text{Ga}(\text{Brbad})]\text{ClO}_4\cdot\text{DMSO}$. An ORTEP drawing of the $[\text{Ga}(\text{Brbad})]^+$ cation in $[\text{Ga}(\text{Brbad})]\text{ClO}_4\cdot\text{DMSO}$ is illustrated in Figure 1 while selected bond distances and angles in the cation are listed in Table 9. Ga^{3+} and In^{3+} were expected to coordinate to the trien-based amine phenols via the four neutral amine nitrogens and two anionic phenolate oxygens to form an N_4O_2 donor set, giving monocationic complexes with an octahedral or distorted octahedral coordination geometry. Considering the steric constraint of the trien backbone, it was expected that the amine phenol ligand should span the octahedral positions around the metal center in a manner such that any two adjacent donor atoms would be coordinated cis to each other. (A coordination environment with two adjacent donor atoms coordinated trans to each other would have an extremely strained trien backbone.) There are, however, four ways in which the linear trien-based amine phenols may span octahedral positions such that adjacent donor atoms are coordinated cis to one another (Chart 2); the mirror image of each is also possible since the structures are all chiral. Space

filling models suggest that structure **A** is the least sterically strained of the four possible structures, which is consistent with an earlier postulation.²²

Crystallographic analysis of $[\text{Ga}(\text{Brbad})]\text{ClO}_4\cdot\text{DMSO}$ confirmed the hexacoordination of the amine phenol ligand to Ga^{3+} through four amine nitrogens and two phenolate oxygens. The complex is monocationic with a doubly deprotonated amine phenol ligand coordinated to Ga^{3+} in a distorted octahedral coordination geometry. N1, N2, O2 occupy one face of the octahedron while N3, N4, O1 occupy the other face. Distortion in the octahedral geometry can be attributed to the steric requirements of the trien backbone, coordination of the four amine nitrogens resulting in three five-membered chelate rings. These five-membered rings restrict the cis angles involving two consecutive nitrogens to an average of 81.6° (N1–Ga–N2 = 82.2(3)°, N2–Ga–N3 = 80.1(3)°, N3–Ga–N4 = 82.4(3)°). Coordination of the phenolate oxygens formed two six-membered chelate rings with cis angles of 90.4(3) and 90.1(3)° for O1–Ga–N1 and O2–Ga–N4, respectively. Distortion in the octahedral geometry can be decreased by replacing the ethylene groups with propylene groups, which would result in the formation of six-membered rings when the ligand is coordinated to a metal center. This is observed in Mn complexes of 1,8-bis(2-hydroxybenzamido)-3,6-diazaoctane and 1,8-bis(2-hydroxybenzamido)-4,7-diazadecane.³⁰ The Mn diazaoctane complex contains two six-membered and three five-membered chelate rings. Replacing two ethylene groups with propylene groups in the diazadecane backbone results in one five-membered ring and four six-membered chelate rings in the Mn diazadecane complex. The cis angles between adjacent donor atoms in the diazadecane complex are closer to 90° than similar angles in the diazaoctane complex. Hence, there is less distortion in the octahedral geometry of the diazadecane complex. This would also be expected in the coordination of Ga^{3+} and In^{3+} with ligands having longer, more flexible amine backbones.

As illustrated in Chart 2, the linear trien-based amine phenols can coordinate a metal center in four possible configurations. Crystallographic analysis of $[\text{Ga}(\text{Brbad})]\text{ClO}_4\cdot\text{DMSO}$ showed that the metal complex assumed the configuration of structure **A**. This is consistent with the postulate that structure **A** is the least sterically demanding of the four possible structures (the halves of the chelating ligand being *mer* to each other).²² Other complexes with similar linear hexadentate ligands such as $[\text{Ni}(\text{sal})_2\text{trien}]$,²⁶ $[\text{Fe}(\text{sal})_2\text{trien}]\text{Cl}\cdot 2\text{H}_2\text{O}$,²⁷ and $[1,8\text{-bis}(2\text{-hydroxybenzamido})\text{-3,6-diazaoctanato}]\text{manganese(IV)}$ ³⁰ also assume configuration **A**. In $[1,10\text{-bis}(2\text{-hydroxybenzamido})\text{-3,6-diazadecanato}]\text{manganese(IV)}$,³⁰ the greater flexibility of the diazadecane ligand allows it to coordinate to Mn(IV) such that the two phenolate oxygens are trans to one another and cis to the amine nitrogens (structure **B**, Chart 2).

The two Ga–O bond lengths were 1.911(6) Å (Ga–O1) and 1.914(6) Å (Ga–O2) while the Ga–N1 and Ga–N4 bond lengths were 2.073(7) and 2.085(7) Å, respectively. These latter distances were shorter than the Ga–N2 and Ga–N3 bond lengths, which were 2.138(8) and 2.153(8) Å, respectively. Steric constraints of the trien backbone caused this difference in Ga–N bond lengths; however, the Ga–N and Ga–O bond lengths were still consistent with the lengths observed in the Ga amine phenol complexes,^{8–10} Ga Schiff base complexes,³¹ and other Ga hexadentate ligand complexes.^{32–36}

(30) Chandra, S. K.; Chakravorty, A. *Inorg. Chem.* **1992**, *31*, 760.

(31) Green, M. A.; Welch, M. J.; Huffman, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 3689.

(32) Kennard, C. H. L. *Inorg. Chim. Acta* **1967**, *2*, 347.

Attempts to grow X-ray quality crystals of an In analogue were unsuccessful; however, the In complexes would probably show a coordination environment similar to that of [Ga(**Brbad**)]⁺. As the ionic radius of In³⁺ in six-coordination (0.80 Å)³⁷ is larger than that of Ga³⁺ (0.62 Å),³⁷ there would likely be an even greater steric strain within the trien backbone as the amine phenol ligand wraps around the larger In³⁺ ion.

Concluding Remarks. A new series of linear amine phenols (**H₂bad**, **H₂Clbad**, **H₂Brbad**) was prepared by the *in situ* reduction of Schiff base compounds formed by condensation reactions of triethylenetetramine (trien) and salicylaldehyde or ring-substituted salicylaldehydes. Acetone adducts (**H₂badAc**, **H₂ClbadAc**, **H₂BrbadAc**) were also prepared by reacting the amine phenols with acetone. These adducts contained two imidazolidine rings, which opened during complexation. Ga and In complexes of trien-based amine phenols were prepared and characterized as monocationic complexes with the metal ion coordinated by a N₄O₂ donor set. Crystallographic analysis of [Ga(**Brbad**)]ClO₄·DMSO showed the Ga³⁺ ion coordinated to four amine nitrogens and two deprotonated phenolate oxygens in a distorted octahedral geometry. Due to the steric constraint of the trien backbone, adjacent donor atoms in the ligand were coordinated *cis* to one another. The coordination environment (structure **A**, Chart 2) assumed by the metal complexes is the least sterically strained of the four possible coordination environments. Other metal complexes with similar ligands also exhibit the same coordination environment.

(33) Restivo, R.; Palenik, G. J. *J. Chem. Soc., Dalton Trans.* **1972**, 341.

(34) Riley, P. E.; Pecoraro, V. L.; Carrano, C. J.; Raymond, K. N. *Inorg. Chem.* **1983**, *22*, 3096.

(35) Moore, D. A.; Fanwick, P. E.; Welch, M. J. *Inorg. Chem.* **1989**, *28*, 1504.

(36) Moore, D. A.; Fanwick, P. E.; Welch, M. J. *Inorg. Chem.* **1990**, *29*, 672.

(37) Shannon, R. D. *Acta Crystallogr.* **1976**, *A32*, 751.

Three five-membered and two six-membered chelate rings were formed by the coordination of the linear trien-based amine phenols to metal ions. It has been postulated that complex stability is closely related to the size of chelate rings and to the size of the metal ion.³⁸⁻⁴⁰ As chelate ring size increases from five to six, stability of metal complexes generally decreases. The larger the coordinated metal ion, the greater the destabilization in the metal complex as the chelate ring size increases from five to six. Molecular mechanics calculations have shown that complexes with small metal ions and M-N bond lengths of approximately 1.6 Å will coordinate with the least strain when the resulting chelate ring is six-membered and that larger metal ions coordinate with the least strain when five-membered chelate rings are formed.³⁸⁻⁴⁰ Trien-based amine phenols, which formed three five-membered rings and two six-membered rings upon complexation, would be expected to form more stable complexes as the size of the metal ion increases from Al³⁺ (0.53 Å) to Ga³⁺ (0.62 Å) to In³⁺ (0.80 Å).³⁷ This conclusion is partially corroborated by the failure to isolate Al complexes; however, stability constant studies would clarify this situation.

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Supplementary Material Available: Complete tables of distances, angles, hydrogen atom parameters, and anisotropic thermal parameters, as well as an ORTEP diagram of the disordered perchlorate anion (5 pages). Ordering information is given on any current masthead page.

IC940609Z

(38) Hancock, R. D. *Prog. Inorg. Chem.* **1989**, *37*, 187.

(39) Hancock, R. D.; Martell, A. E. *Chem. Rev.* **1989**, *89*, 1875.

(40) Hancock, R. D. *J. Chem. Educ.* **1992**, *69*, 615.