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Monohydroxamic acids and bridging dihydroxamic acids as chelators to ruthenium(III) and as nitric oxide donors: syntheses, speciation studies and nitric oxide releasing investigation†

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The synthesis and spectroscopic characterisation of novel mononuclear Ru^{III}(edta)(hydroxamato) complexes of general formula [Ru(H_2edta)(*mono*ha)] (where *mono*ha = 3- or 4-NH_2, 2-, 3- or 4-Cl and 3-Me-phenylhydroxamato), as well as the first example of a Ru^{III}-*N*-aryl aromatic hydroxamate, [Ru(H_2edta)(*N*-Me-bha)]·H_2O (*N*-Me-bha = *N*-methylbenzohydroxamato) are reported. Three dinuclear Ru^{III} complexes with bridging dihydroxamato ligands of general formula [{Ru(H_2edta)}$_2$(μ-*di*ha)] where *di*ha = 2,6-pyridinedihydroxamato and 1,3- or 1,4-benzodihydroxamato, the first of their kind with Ru^{III}, are also described. The speciation of all of these systems (with the exception of the Ru–1,4-benzodihydroxamic acid and Ru–*N*-methylbenzohydroxamic systems) in aqueous solution was investigated. We previously proposed that nitrosyl abstraction from hydroxamic acids by Ru^{III} involves initial formation of Ru^{III}-hydroxamates. Yet, until now, no data on the rate of nitric oxide (NO) release from hydroxamic acids has been published. We now describe a UV-VIS spectroscopic study, where we monitored the decrease in the ligand-to-metal charge-transfer band of a series of Ru^{III}-monohydroxamates with time, with a view to gaining an insight into the NO-releasing properties of hydroxamic acids.

Introduction

Hydroxamic acids RC(O)NHOH have emerged in recent years as a class of compounds that can fulfil a variety of roles in biology and medicine, many of which are as a result of their enzyme-inhibitory properties.[1,2] The versatile biological activity of hydroxamic acids is undoubtedly due to their ability to form stable metal chelates,[1,2] and possibly their NO-releasing properties.[3] In addition, when deprotonated, the hydroxamate anion ($RCOHNO^-$) can form salt linkages in their complexes with proteins, and when neutral (RCOHNOH) may engage in important hydrogen-bonding interactions.[1]

The powerful metal-chelating ability of hydroxamic acids has also been utilised to construct a diverse host of fascinating metal complexes including hydroxamates,[1,4–8] hydroximates[1,4,9] and examples in supramolecular chemistry such as metallacrowns,[1,10,11] coordination polymers[12] and tetrahedral cluster complexes.[13]

One of the first physiological roles of hydroxamic acids was associated with their use as siderophores, a class of low molecular weight iron (Fe)-sequestering agents involved in microbial iron transport. As a result, the chemistry of Fe^{III}-hydroxamato complexes has been extensively studied, with numerous X-ray structural reports of and determination of stability constants for Fe^{III} complexes with synthetic and naturally occurring hydroxamic acids. Typically, hydroxamic acids coordinate Fe^{III} in an *O*,*O*′-bidentate manner to form stable metal chelates with characteristically high formation constants. Desferal, for example, a trihydroxamic acid used clinically as an Fe scavenger, coordinates to Fe^{III} *via* its three hydroxamato moieties, forming an Fe^{III}-trishydroxamate with log $\beta \sim 30$.[1]

Despite such an active interest in hydroxamato complexes of Fe^{III}, surprisingly there is only one literature report to date on their complexes with Ru^{III}. In this, the first structurally characterised Ru^{III} hydroxamato complex, [Ru(H_2edta)(2-MeO-pha)] (where 2-MeO-pha is 2-methoxyphenylhydroxamato) (Fig. 1), and the synthesis and spectroscopic characterisation of several others are reported.[14]

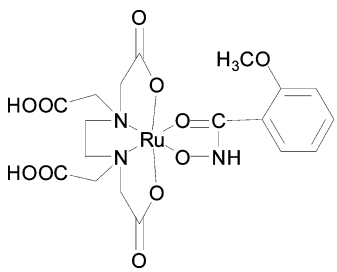

Fig. 1 Structure of [Ru(H_2edta)(2-OMe-pha)].

The speciation and stability constants for several mononuclear Ru^{III}-hydroxamato complexes were also reported in addition to their relative affinity for Ru^{III} over Fe^{III}.[14] We now report the syntheses and spectroscopic characterisation of three dinuclear Ru^{III}-complexes with bridging dihydroxamato ligands, the first of their kind with Ru^{III} to be reported as well as a series of novel mononuclear Ru^{III}-hydroxamato complexes, including the first

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example of a Ru^{III}-*N*-aryl aromatic hydroxamato derivative. The speciation of all of these systems (with the exception of the Ru–1,4-benzodihydroxamic acid and the Ru–*N*-methylbenzohydroxamic acid systems) in aqueous solution was investigated and is also herein reported.

We previously proposed that nitrosyl abstraction from hydroxamic acids by K[Ru(Hedta)Cl] involves initial formation of Ru^{III}-hydroxamato complexes with the subsequent formation of the Ru^{II}-nitrosyl $[Ru^{II}(Hedta)(NO)Cl]^-$ and the corresponding carboxylic acid.[3] Yet, until now, no data on the rate of NO release from hydroxamic acids have been published. We have carried out a UV-VIS spectroscopic investigation in which we monitored the decrease in the hydroxamato ligand-to-Ru metal charge-transfer band of a series of Ru^{III}-hydroxamato complexes with time, with a view to gaining an insight into the NO-releasing properties of hydroxamic acids.

Experimental

Materials and instrumentation

Benzohydroxamic acid (bhaH), acetohydroxamic acid (achaH), benzoyl chloride, the ester reagents and deuterated solvents were all purchased from Aldrich and used without further purification. $RuCl_3 \cdot xH_2O$ was kindly donated by Johnson Matthey. IR spectra were recorded as KBr discs (4000–400 cm^{-1}) on a Mattson Genesis II CSI FTIR spectrometer and the spectra analysed using WinFirst software. ^1H NMR spectra were recorded on a Bruker Avance 400 MHz NMR spectrometer and the spectra analysed using TopSpin 1 software. The residual undeuterated DMSO signal at 2.505 ppm or the Me_4Si signal were used as internal references. UV-VIS spectra were performed on a Helios α Thermo Spectronic Spectrophotometer in a quartz cell. Liquid chromatography-mass spectrometry experiments were performed on a Quattro Micro quadrupole electrospray mass spectrometer (Micromass, Waters Corp., USA); 10 μL of the samples were injected in 300 μL of acetonitrile–water (60 : 40, v/v). The mass spectrometry data were acquired both in positive and negative ion modes. Magnetic measurements were carried out on polycrystalline samples using a Sherwood Scientific Magnetic Susceptibility Balance. Elemental analysis (C, H, N, Cl & K) were performed at the Microanalytical Laboratory, School of Chemistry and Chemical Biology, University College Dublin.

Syntheses

Synthesis of *N*-aryl aromatic hydroxamic acid

N-Methylbenzohydroxamic acid (*N*-Me-bhaH)[15]

N-Methylhydroxylamine hydrochloride (2.36 g, 28 mmol) was added to sodium carbonate (3.65 g, 34 mmol) in deionised water (50 cm^3) under nitrogen. The solution was covered with diethyl ether (20 cm^3). Benzoyl chloride (4.06 cm^3, 35 mmol) in diethyl ether (30 cm^3) was added dropwise over 10 minutes to the stirring heterogeneous mixture in an ice–salt bath. The mixture was stirred and then cooled for a further 30 minutes, after which 20% sodium hydroxide (12 cm^3) was added. The aqueous layer was neutralised to pH 7 with 6 M HCl, saturated with sodium chloride and extracted five times with chloroform. The chloroform was dried with magnesium sulfate and then removed *in vacuo* affording a tan-coloured oil, which was purified by column chromatography on silica using ethyl acetate–*n*-heptane as eluent to give *N*-Me-bhaH (0.95 g, 23%) as a colourless oil: δ_H (400 MHz; $CDCl_3$) 7.31–7.43 (5H, m, ar H), 2.94 (s, 3H, CH_3).

Syntheses of mono- and dihydroxamic acids

A series of mono- and dihydroxamic acids, listed in Table 1, were synthesised by reaction of hydroxylamine with the corresponding methyl or ethyl esters according to the method described for 1,4-benzodihydroxamic acid below. ^1H NMR and selected IR data and elemental analyses for each of the hydroxamic acids synthesised may also be found in Table 1.

1,4-Benzodihydroxamic acid, terephthalohydroxamic acid (1,4-bhaH$_2$)

Hydroxylamine hydrochloride (6.3 g, 90 mmol) was mixed with sodium hydroxide (7.2 g, 180 mmol) in deionised water (45 cm^3). The solution was then added to dimethyl terephthalate (5.8 g, 30 mmol) in methanol (50 cm^3). The resulting solution was stirred for 72 hours at 40 °C and was acidified to pH 5.5 using 5% HCl. The solvent was removed *in vacuo* yielding a yellow solid. Methanol (60 cm^3) was added and sodium chloride filtered. The solvent was removed *in vacuo* yielding a white solid, which was recrystallised from water to give 1,4-bhaH$_2$ (3.4 g, 58%) as a white crystalline solid (Found: C, 48.7; H, 4.1; N, 14.1%. Calc. for $C_8H_8N_2O_4$: C, 49.0; H, 4.0; N, 14.3%); δ_H (400 MHz, DMSO): 11.33 (2H, br s, OH), 9.14 (2H, br s, NH) and 7.81 (4H, s, aromatic H); ν_{max}/cm^{-1} 3288vs (NH), 2730b (OH), 1649vs, 1612vs (CO) and 1562s (CN).

Syntheses of Ru^{III} complexes

K[Ru(Hedta)Cl]·2H$_2$O (1)

K[Ru(Hedta)Cl]·2H$_2$O (4.6 g, 63%) was prepared by modification of a literature method[16] (Found: C, 23.8; H, 3.3; N, 5.4; Cl, 7.0; K, 7.6%. Calc. for $RuC_{10}H_{17}N_2O_{11}ClK$: C, 24.0; H, 3.4; N, 5.6; Cl, 7.1; K, 7.8%); ν_{max}/cm^{-1} 3410s (OH), 2992s, 2942s (CH, CH_2), 1726s (CO, free glycine arm), and 1632s (CO, bound glycinato arms).

[Ru(H$_2$edta)(*N*-Me-bha)]·H$_2$O (2)

An ethanolic solution (10 cm^3) of *N*-methylbenzohydroxamic acid (*N*-Me-bha) (0.22 g, 1.45 mmol) was added to an aqueous solution (25 cm^3) of K[Ru(Hedta)Cl]·2H$_2$O (0.56 g, 1.12 mmol). The reaction was stirred for 2 hours. A red precipitate **2** (0.56 g, 83%) was filtered and dried over P_2O_5 (Found: C, 38.5; H, 4.3; N, 7.4%. Calc. for $RuC_{18}H_{24}N_3O_{11}$: C, 38.6; H, 4.3; N, 7.5%); ν_{max}/cm^{-1} 3494vs (NCH_3), 1722vs (CO, free glycine arms), 1640vs (CO, glycinato) and 1611vs (CO, hydroxamato); ESI-MS *m*/*z*: 543 ($[M + H]^+$); $\mu_{eff} = 1.89\ \mu_B$.

Complexes **4–14** were synthesised according to the method described for [{Ru(H$_2$edta)}$_2$(μ-1,4-bha)]·2H$_2$O below. In all cases the reaction solutions were concentrated *in vacuo* before being left overnight in a refrigerator whereupon solids precipitated over time. Numerous attempts were made to isolate crystals suitable for an X-ray crystallographic study but to no avail.

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Table 1 Hydroxamic acids synthesised with yields, elemental analyses and selected IR and ^{1}H NMR data

			Elemental analysis: Calc. (found)%			Selected IR data (KBr disc) ν_{max}/cm^{-1}				
Name	Abbreviation	Yield	C	H	N	NH	OH	CO	CN	Selected NMR data δ_H (400MHz, DMSO)
1,4-Benzodihydroxamic acid, (terephthalohydroxamic acid)	1,4-bhaH_2	58%	49.0 (48.7)	4.1 (4.1)	14.3 (14.2)	3288vs	2730b	1649vs, 1612vs	1562s	11.33 (2H, br s, OH), 9.14 (2H, br s, NH) and 7.81 (4H, s, ar H)
1,3-Benzodihydroxamic acid, (isophthalohydroxamic acid)	1,3-bhaH_2	51%	49.0 (48.8)	4.1 (4.1)	14.3 (14.2)	3316vs	2797b	1657vs, 1625vs	1564vs	11.16 (2H, br s, OH), 9.09 (2H, br s, NH), 8.20 (1H, s, ar H), 7.88 (2H, dd, ^3J 7.8 & ^4J 1.5 Hz, ar H) and 7.53 (1H, t, ^3J 7.8, ar H)
2,6-Pyridinedihydroxamic acid	2,6-pyhaH_2	66%	42.65 (42.4)	3.6 (3.3)	21.3 (21.5)	3284vs	2888b	1669vs, 1646vs	1564s	11.84 (2H, br s, OH), 9.32 (2H, br s, NH) and 8.12–8.23 (3H, m, ar H)
2-Aminophenylhydroxamic acid	2-NH_2-phaH	63%	55.25 (55.1)	5.3 (5.2)	18.4 (18.4)	3403vs, 3322vs, 3164s	2864b	1637vs, 1605vs	1561s	10.93 (1H, br s, OH), 8.87 (1H, br s, NH), 7.31 (1H, dd, ^3J 7.6 and ^4J 1.5, ar H), 7.13 (1H, dt, ^3J 7.6 & ^4J 1.5, ar H), 6.70 (1H, d, ^3J 7.6, ar H), 6.48 (1H, t, ^3J 7.6 ar H) and 6.23 (2H, br s, NH_2)
3-Aminophenylhydroxamic acid	3-NH_2-phaH	76%	55.25 (55.1)	5.3 (5.2)	18.4 (18.3)	3415vs, 3336vs, 3280s	2788b	1623vs, 1583vs	1575s	10.97 (1H, br s, OH), 8.88 (1H, br s, NH), 7.04 (1H, t, ^3J 8.0, ar H), 6.95 (1H, s, ar H), 6.83 (1H, d, ^3J 8.0, ar H) 6.65 (1H, dd, ^3J 8.0 & ^4J 1.5, ar H) and 5.25 (2H, br s, NH_2)
4-Aminophenylhydroxamic acid	4-NH_2-phaH	55%	55.25 (55.0)	5.30 (5.2)	18.4 (18.3)	3414vs, 3337vs, 3281s	2814b	1648vs, 1603vs	1537s	10.75 (1H, br s, OH), 8.68 (1H, br s, NH), 7.47 (2H, d, ^3J 8.5, ar H), 6.53 (2H, d, ^3J 8.5, ar H) and 5.61 (2H, br s, NH_2)
2-Chlorophenylhydroxamic acid	2-Cl-phaH	72%	49.0 (48.7)	3.5 (3.3)	8.2 (8.2)	3228s	2881b	1631vs, 1594vs	1542s	10.97 (1H, br s, OH), 9.25 (1H, br s, NH) and 7.39–7.52 (4H, m, ar H)
3-Chlorophenylhydroxamic acid	3-Cl-phaH	65%	49.0 (48.7)	3.5 (3.4)	8.2 (7.9)	3295vs	2873b	1659vs, 1621vs	1552vs	11.35 (1H, br s, OH), 9.18 (1H, br s, NH), 7.78 (1H, s, ar H), 7.72 (1H, dd, ^3J 7.9 & ^4J 1.4, ar H), 7.60 (1H, dd, ^3J 7.9 & ^4J 1.4, ar H) and 7.50 (1H, t, ^3J 7.9, ar H)
4-Chlorophenylhydroxamic acid	4-Cl-phaH	59%	49.0 (48.8)	3.5 (3.4)	8.2 (7.9)	3295vs	2773b	1649vs, 1608vs	1545vs	11.19 (1H, br s, OH), 9.01 (1H, br s, NH), 7.63 (2H, d, ^3J 8.4, ar H) and 7.39 (2H, d, ^3J 8.4, ar H)
2-Methylphenylhydroxamic acid	2-Me-phaH	63%	63.6 (63.3)	6.0 (5.9)	9.3 (9.0)	3228s	2923	1627vs, 1597vs	1555s	10.82 (1H, br s, OH), 9.06 (1H, br s, NH), 7.33 (1H, dt, ^3J 7.4 & ^4J 1.5, ar H), 7.20–7.27 (3H, m, ar H) and 2.33 (3H, s, CH_3)
3-Methylphenylhydroxamic acid	3-Me-phaH	70%	63.6 (63.4)	6.0 (6.0)	9.3 (9.1)	3281s	2883b	1645vs, 1597vs	1555s	11.18 (s, 1H, OH), 9.03 (s, 1H, NH), 7.58 (1H, s, ar H), 7.54 (1H, t, ^3J 5.0, ar H), 7.33 (2H, d, ^3J 5.0, ar H) and 2.34 (3H, s, CH_3)
4-Methylphenylhydroxamic acid	4-Me-phaH	58%	63.6 (63.7)	6.0 (5.9)	9.3 (9.1)	3295s	2777b	1649vs, 1614vs	1552s	11.16 (1H, br s, OH), 8.99 (1H, br s, NH), 7.66 (2H, d, ^3J 8.2, ar H), 7.25 (2H, d, ^3J 8.2, ar H) and 2.34 (3H, s, CH_3)
4-Dimethylaminophenyl-hydroxamic acid	4-NMe_2-phaH	73%	60.0 (59.9)	6.7 (6.6)	15.55 (15.3)	3250 s	2915b	1611vs	1515s	10.73 (1H, br s, OH), 8.58 (1H, br s NH), 7.49 (2H, d, ^3J 8.6, ar H), 6.54 (2H, d, ^3J 8.6, ar H) and 2.83 (6H, s N-CH_3)

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[{Ru(H$_2$edta)}$_2$(μ-1,4-bha)]·2H$_2$O (3)

An aqueous solution (20 cm^3) of 1,4-benzodihydroxamic acid (0.15 g, 0.75 mmol) was added to an aqueous solution (15 cm^3) of K[Ru(Hedta)Cl]·2H$_2$O (0.75 g, 1.50 mmol) in deionised water (15 cm^3). The reaction was stirred for 3 hours, concentrated *in vacuo* and left to stand in a refrigerator overnight. A red precipitate **3** (0.70 g, 46%) was filtered and dried over P_2O_5 (Found: C, 33.1; H, 4.0; N, 8.5%. Calc. for $Ru_2C_{28}H_{38}N_6O_{22}$: C, 33.2; H, 3.8; N, 8.3%); ν_{max}/cm^{-1} 3288vs (NH), 1724vs (CO, free glycine arms), 1668vs (CO, glycinato) and 1609vs (CO, hydroxamato); ESI-MS *m*/*z*: 977 ([M–H]$^-$); $\mu_{eff} = 2.16\,\mu_B$.

[{Ru(H$_2$edta)}$_2$(μ-1,3-bha)]·4H$_2$O (4)

Yield: 0.48 g, 80%. (Found: C, 31.8; H, 3.7; N, 8.0%. Calc. for $Ru_2C_{28}H_{42}N_6O_{24}$: C, 31.5; H, 3.4; N, 7.8%); ν_{max}/cm^{-1} 3213s (NH), 1732vs (CO, free glycine arms) and 1639vs (CO, glycinato and hydroxamato); ESI-MS *m*/*z*: 977 ([M–H]$^-$).

[{Ru(H$_2$edta)}$_2$(μ-2,6-pyha)]·4H$_2$O (5)

Yield: 0.29 g, 28%. (Found: C, 30.6; H, 3.5; N, 9.0%. Calc. for $Ru_2C_{27}H_{41}N_7O_{24}$: C, 30.9; H, 3.9; N, 9.3%); ν_{max}/cm^{-1} 3265vs (NH), 1731vs (CO, free glycine arms) and 1641vs (CO, glycinato and hydroxamato); ESI-MS *m*/*z*: 978 ([M–H]$^-$).

[Ru(H$_2$edta)(bha)]·2H$_2$O (6)

Yield: 0.55 g, 68%. (Found: C, 36.4; H, 4.1; N, 7.3%. Calc. for $RuC_{17}H_{24}N_3O_{12}$: C, 36.2; H, 4.3; N, 7.5%); ν_{max}/cm^{-1} 3195s (NH), 1731s (CO, free glycine arms) and 1634vs (CO, glycinato and hydroxamato); $\mu_{eff} = 1.76\,\mu_B$.

[Ru(H$_2$edta)(3-NH$_2$-pha)]·2H$_2$O (7)

Yield: 0.12 g, 53%. (Found: C, 35.2; H, 4.2; N, 10.0%. Calc. for $RuC_{17}H_{25}N_4O_{12}$: C, 35.3; H, 4.4; N, 9.7%); ν_{max}/cm^{-1} 3264b (NH), 1729s (CO, free glycine arms) and 1624vs (CO, glycinato and hydroxamato); ESI-MS *m*/*z*: 544 ([M + H]$^+$).

[Ru(H$_2$edta)(4-NH$_2$-pha)]·4H$_2$O (8)

Yield: 0.54 g, 61%. (Found: C, 32.9; H, 4.5; N, 9.0%. Calc. for $RuC_{17}H_{29}N_4O_{14}$: C, 33.2; H, 4.8; N, 9.1%); ν_{max}/cm^{-1} 3442vs, 3380vs, 3233s (NH), 1730s (CO, free glycine arms) and 1629vs (CO, glycinato and hydroxamato).

[Ru(H$_2$edta)(2-Cl-pha)]·H$_2$O (9)

Yield: 0.084 g, 38%. (Found: C, 35.5; H, 3.7; N, 7.2%. Calc. for $RuC_{17}H_{21}N_3ClO_{11}$: C, 35.2; H, 3.65; N, 7.25%); ν_{max}/cm^{-1} 3211s (NH), 1730s (CO, free glycine arms) and 1635vs (CO, glycinato and hydroxamato).

[Ru(H$_2$edta)(3-Cl-pha)]·2H$_2$O (10)

Yield: 0.26 g, 43%. (Found: C, 34.3; H, 3.4; N, 6.8%. Calc. for $RuC_{17}H_{23}N_3ClO_{12}$: C, 34.15; H, 3.9; N, 7.0%); ν_{max}/cm^{-1} 3167s (NH), 1732s (CO, free glycine arms) and 1650vs (CO, glycinato and hydroxamato); ESI-MS *m*/*z*: 563 ([M + H]$^+$).

[Ru(H$_2$edta)(4-Cl-pha)]·2H$_2$O (11)

Yield: 0.32 g, 55%. (Found: C, 34.4; H, 3.6; N, 6.8%. Calc. for $RuC_{17}H_{23}N_3ClO_{12}$: C, 34.15; H, 3.9; N, 7.0%); ν_{max}/cm^{-1} 3297vs (NH), 1731s (CO, free glycine arms), 1648vs (CO, glycinato) and 1610s (CO, hydroxamato).

[Ru(H$_2$edta)(2-Me-pha)]·2H$_2$O (12)

Yield: 0.045 g, 20%. (Found: C, 37.1; H, 4.3; N, 6.8%. Calc. for $RuC_{18}H_{26}N_3O_{12}$: C, 37.4; H, 4.5; N, 7.3%); ν_{max}/cm^{-1} 3228vs (NH), 1730s (CO, free glycine arms) and 1630vs (CO, glycinato and hydroxamato).

[Ru(H$_2$edta)(3-Me-pha)]·2H$_2$O (13)

Yield: 0.053 g, 24%. (Found: C, 37.2; H, 4.4; N, 7.0%. Calc. for $RuC_{18}H_{26}N_3O_{12}$: C, 37.4; H, 4.5; N, 7.3%); ν_{max}/cm^{-1} 3221vs (NH), 1730 s (CO, free glycine arms) and 1632vs (CO, glycinato and hydroxamato); ESI-MS *m*/*z*: 543 ([M + H]$^+$).

[Ru(H$_2$edta)(4-Me-pha)]·2H$_2$O (14)

Yield: 0.096 g, 40%. (Found: C, 37.3; H, 4.2; N, 7.0%. Calc. for $RuC_{18}H_{26}N_3O_{12}$: C, 37.4; H, 4.5; N, 7.3%); ν_{max}/cm^{-1} 3228vs (NH), 1730s (CO, free glycine arms) and 1630vs (CO, glycinato and hydroxamato).

Syntheses of Ru^{II}-nitrosyl complexes

Reaction of K[Ru(Hedta)Cl]·2H$_2$O with achaH, bhaH, 2-, 3- or 4-NH$_2$-phaH, 2-, 3- or 4-Cl-phaH and 2-, 3- or 4-Me-phaH and 2,6-pyhaH$_2$ under reflux, resulted in the facile formation of the brown Ru^{II}-nitrosyl adduct of formula K[Ru(Hedta)(NO)Cl] regardless of hydroxamic acid used. In contrast, 1,3- and 1,4-bhaH$_2$, when reacted with K[Ru(Hedta)Cl] under reflux, gave the corresponding red Ru^{III}-dihydroxamates in high yield and the nitrosyl adduct could only be isolated as a minor product upon purification of the filtrates using a sephadex LH20 column. A typical synthesis is described below. Reaction of K[Ru(Hedta)Cl]·2H$_2$O with *N*-Me-phaH did not produce a nitrosyl product, rather it resulted in the formation of [Ru(H$_2$edta)(*N*-Me-bha)]·H$_2$O **2** only.

K[Ru(Hedta)(NO)Cl]·H$_2$O (15)

An aqueous solution (20 cm^3) of benzohydroxamic acid (bhaH) (0.41 g, 3.0 mmol) was added to an aqueous solution (15 cm^3) of K[Ru(Hedta)Cl]·2H$_2$O (0.5 g, 1.0 mmol), resulting in a red solution. Upon heating, the reaction solution turned brown in colour. It was refluxed for ~30 min and then concentrated *in vacuo* (10 cm^3). After overnight refrigeration a white precipitate was filtered and dried. The brown filtrate was taken to dryness on a rotary evaporator. The resulting brown precipitate was stirred in a 1 : 1 diethyl ether–ethyl acetate suspension overnight. The brown product was filtered, purified on a sephadex column LH20 using water as eluent to give **15** (0.29 g, 58%) as a brown solid (Found: C, 23.4; H, 2.9; N, 8.5; Cl, 6.9; K, 7.4%. Calc. for $RuC_{10}H_{15}N_3ClKO_{10}$: C, 23.4; H, 2.95; N, 8.2; Cl, 6.9; K, 7.6%); δ_H (400 MHz; D_2O; Me_4Si) 4.43 (d, 2H, CH_2 glycine), 4.34 (s, 2H, CH_2 glycine), 4.09 (2H, s, CH_2 glycine), 3.84 (2H, s, CH_2 glycine) 3.61 (4H, m,

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CH_2 ethylenediamine); δ_C (400 MHz; D_2O; Me_4Si) 181.8, 178.5 (CO, glycinato), 177.7, 168.8 (CO, free glycine), 65.45, 65.4, 64.7, 64.3 (CH_2 glycinato), 62.8, 60.4 (CH_2 ethylenediamine); ν_{max}/cm^{-1} 3345 s (OH), 2986 s, 2947 s (CH, H_2edta), 1894vs (NO), 1726s (CO, free glycine arms) and 1649b (CO, glycinato); ESI-MS *m/z*: 456 ($[M–H]^-$).

Potentiometric and spectrophotometric studies

The pH-metric titrations were carried out on a Molspin pH meter and titration controller with Thermo Russell CMAW711 combined electrode and Hamilton syringe autoburette. All measurements were carried out using solutions of 0.1 mol dm^{-3} ionic strength (KNO_3) at 25 ± 0.1 °C. Carbonate-free KOH solution of known concentrations (*ca.* 0.2 mol dm^{-3}), standardised with potassium hydrogen phthalate,[17] were used as titrant. In the Ru^{III}(edta) hydroxamic acid titrations readings were taken every 3 seconds to a precision of 0.001 pH units using the Molspin titrator set on 'slow reaction rate'. A minimum number of readings is used to calculate the standard deviation and this is compared to the required precision. This process is repeated between 9 and 900 times until the standard deviation is less than the required precision. This ensures that pH data are collected for a fully equilibrated system. Each titration curve was carried out in triplicate and 120 points per titration were used to calculate the experimental equilibrium constants.

The electrode system was calibrated by the method of Irving *et al.*[18] ($pK_w = 13.831$) so that the pH-meter readings could be converted into hydrogen ion concentration. For the Ru^{III} systems sufficient time was allowed for equilibration prior to pH measurements.

The pK_a values of the hydroxamic acids and of the aqueous K[Ru(Hedta)Cl]·$2H_2O$ system were determined by titrating solutions (~2.0×10^{-3} mol dm^{-3}) in HNO_3 (5.0×10^{-3} mol dm^{-3}) with a KOH solution of known concentration (0.19807 mol dm^{-3}). This method was also used to determine the exact concentration of the ligand and metal stock solutions. Stability constants of the Ru^{III}-edta-hydroxamato complexes were determined by pH-metric methods using ligand concentrations in the range 1×10^{-3} to 4×10^{-3} mol dm^{-3}. The resulting data were analysed using HYPERQUAD2000.[19]

UV-VIS spectroscopic investigation

A UV-VIS spectroscopic investigation was performed at 50 °C on a Thermo Spectronic Helios α UV-Vis spectrophotometer equipped with a thermostatted cell. The reduction in absorbance at λ_{max} corresponding to the hydroxamato ligand-to-Ru^{III} metal charge transfer (LMCT) band of the Ru^{III}-hydroxamato species $[Ru(edta)(mono\text{ha})]^{2-}$ (where *mono*ha is acha, bha, 2-, 3- or 4-NH_2-pha, 3-Me-pha) was followed. Typical experimental conditions were pH 4.50, ligand to metal ratio of 10 : 1, [Ru] = 2.00 mM and $I = 0.20$ KCl thus ensuring good pseudo-first-order plots of $\ln(A_t - A_\infty)$ *versus* time where A_t and A_∞ are the absorbances at time *t* and infinity, respectively. The metal complex solutions were freshly prepared before each experiment. The temperature (± 0.5 °C) of the cell housing was regulated by circulation of thermostatted water.

Results and discussion

Synthesis and spectroscopic characterisation of hydroxamic acids and their Ru^{III}-hydroxamato complexes

Hydroxamic acids

The hydroxamic acids were synthesised according to literature methods,[20] by reaction of hydroxylamine with the corresponding carboxylic methyl or ethyl esters, with the exception of *N*-methylbenzohydroxamic acid, which was synthesised from a carboxylic acid chloride.[15] They were obtained in good yields (~50–80%) and high purity, and were characterised by elemental analysis, IR and ^{1}H NMR spectroscopy.

Selected IR stretches are given in Table 1. Occasionally, two sharp stretches corresponding to the symmetric and asymmetric ν_{CO} are observed but typically only one broad band appears due to intramolecular hydrogen bonding.[21] The ν_{NH} of the hydroxamic acid is generally observed between 3150 and 3350 cm^{-1}. The broad ν_{OH} of the hydroxamic acid may be attributed to intermolecular hydrogen bonding and is in the main observed in the range 2730 to 2930 cm^{-1}. These values concur with previously reported literature values.[21]

^{1}H NMR spectra for the hydroxamic acids in d^6 DMSO show the hydroxamic acid NH and OH resonances at *ca.* 9 and 11 ppm, respectively. The appearance of these resonances are very much concentration-dependent due to intermolecular hydrogen bonding at high concentrations.

Ru complexes

K[Ru(Hedta)Cl]·$2H_2O$

Previous attempts to synthesise Ru^{III}-hydroxamato complexes using $RuCl_3 \cdot xH_2O$ were hampered by the formation of ill-defined oligomeric products. Therefore with a view to synthesising and characterising Ru^{III}-hydroxamato derivatives, a well-characterised Ru^{III} complex K[Ru(Hedta)Cl]·$2H_2O$ was selected where the ligand $Hedta^{3-}$ is pentadentate with one uncoordinated and protonated glycine moiety. It was prepared by modification of a literature method[16] and obtained in good yield (63%) and high purity. Its IR spectrum exhibits two ν_{CO} stretches; the first, a broad band at 1632 cm^{-1}, is attributed to the carbonyl groups of the Ru-bound glycinato groups and the second, a very distinct sharp band at 1726 cm^{-1}, attributed to the carbonyl group of the protonated free glycine arm of Hedta.[22]

Mononuclear Ru^{III}-hydroxamato complexes

K[Ru(Hedta)Cl] rapidly forms the aqua species when dissolved in water and exists predominantly in its most labile form $[Ru^{III}(edta)(H_2O)]^-$ between pH 5–6.[23] Reaction of an excess of hydroxamic acid with $[Ru^{III}(edta)(H_2O)]^-$ in aqueous solution afforded the corresponding Ru^{III}-monohydroxamato complexes of general formula $[Ru(H_2edta)(mono\text{ha})]$ (*mono*ha = bha, 3- or 4-NH_2-pha, 2-, 3- or 4-Cl-pha, 2-, 3- or 4-Me-pha, NMe-pha) in varying yields but high purity, Scheme 1. All complexes were characterised by IR spectroscopy, elemental analysis and in certain instances by electrospray ionisation mass spectroscopy (ESI-MS) and magnetic susceptibility measurements.

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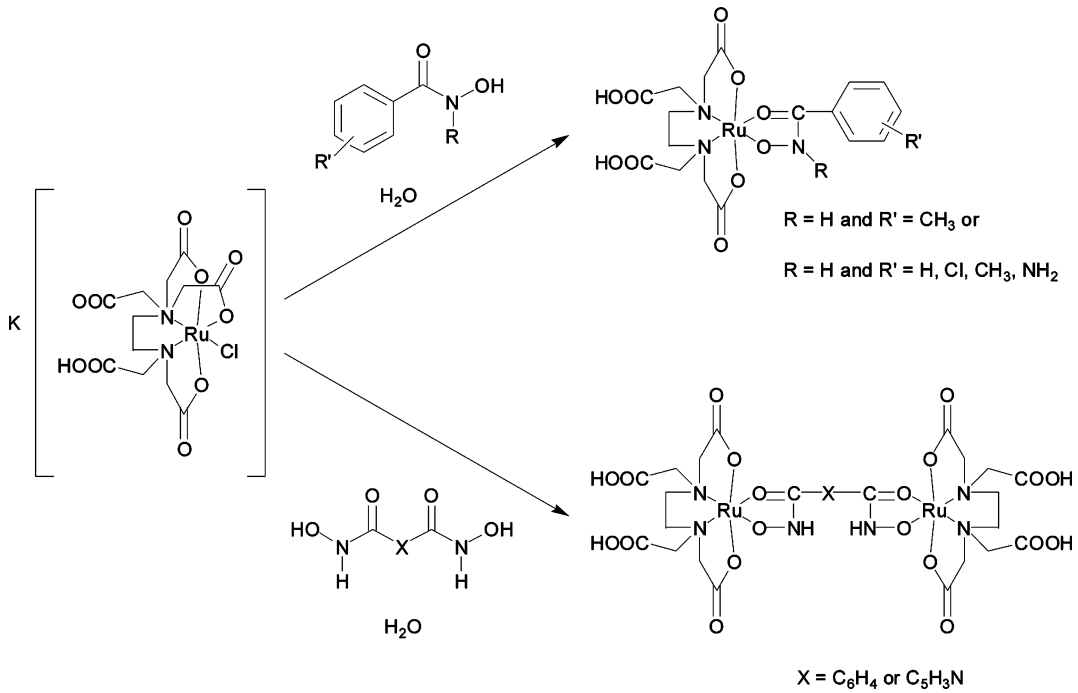

Scheme 1

Although numerous attempts were made to isolate crystals suitable for an X-ray crystallographic study, only crystals of [Ru(H$_2$edta)(2-OMe-pha)]·2H$_2$O ever materialised, the crystal structure of which was previously reported.[14] Nevertheless, comparison of the IR spectra of our complexes with the IR spectrum of [Ru(H$_2$edta)(2-OMe-pha)]·2H$_2$O, assisted in the successful characterisation of the Ru^{III}-hydroxamato complexes synthesised.

The coordination geometry of [Ru(H$_2$edta)(2-OMe-pha)]·2H$_2$O is a slightly distorted octahedron as expected due to the presence of different donor atoms. H$_2$edta is present as a 2*N*, *trans*-2*O*-(dicarboxylato) tetradentate ligand with two fully protonated uncoordinated carboxylic acid moieties. The hydroxamato ligand, 2-MeO-pha, is coordinated to the Ru^{III} centre in typical (*O*,*O*′)-bidentate fashion.[14]

The IR spectra of the Ru^{III}-hydroxamato complexes display three distinctive ν_{CO} bands. Using [Ru(H$_2$edta)(4-Cl-pha)]·2H$_2$O as a representative example, the band at 1610 cm^{-1} is attributed to the hydroxamato carbonyl and is approximately 40 cm^{-1} less than that observed in the spectrum of the free ligand, indicative of hydroxamato coordination. The ν_{CO} at 1648 cm^{-1} and at 1731 cm^{-1} can be assigned to the carbonyl groups of the metal-bound glycinato and glycine arms of edta, respectively. In most cases the ν_{CO} of the hydroxamato ligand and bound glycinato arms of edta are merged and appear as one broad band instead of the expected two sharp, distinct bands. A hydroxamato ν_{NH} is also observed at 3297 cm^{-1}. In general the spectra of the Ru^{III}-hydroxamato complexes display ν_{NH} from *ca.* 3200 to 3350 cm^{-1} while [Ru(H$_2$edta)(*N*-Me-bha)] displays a strong ν_{CH} of the hydroxamato N–CH$_3$ group at 3494 cm^{-1}. The IR spectra of the Ru^{III}-hydroxamato complexes exhibit the same overall pattern as was evidenced for [Ru(H$_2$edta)(2-OMe-pha)]·2H$_2$O, indicating that they all have similar structures, particularly with respect to denticity and protonation state of the edta ligand, hydroxamato binding mode and geometry of the complexes. They are also in agreement with previously reported data.[14] Selected mononuclear Ru^{III}-hydroxamato complexes were further identified by ESI-MS in the positive mode. Mass peaks at 543, 544, 563 and 543 amu are observed for [Ru(H$_2$edta)(*N*-Me-bha)] (542), [Ru(H$_2$edta)(3-NH$_2$-pha)] (543), [Ru(H$_2$edta)(3-Cl-pha)] (562) and [Ru(H$_2$edta)(3-Me-pha)] (542), respectively, and all of which display the correct isotopic abundances. The room temperature μ_{eff} of the mononuclear [Ru(H$_2$edta)(bha)]·2H$_2$O and [Ru(H$_2$edta)(*N*-Me-bha)]·H$_2$O are 1.79 μ_B and 1.89 μ_B, respectively, and fall within the range of 1.7 to 2.3 μ_B, typical of a low-spin paramagnetic Ru^{III} complex with an electron configuration $t_{2g}^5e_g^0$ at this temperature.

The Ru^{III}-hydroxamato complexes of bhaH and the monosubstituted aromatic derivatives 3- and 4-NH$_2$-phaH, 2-, 3- and 4-Cl-phaH, 2-, 3- and 4-Me-phaH, are schematically represented by the general formula [Ru(H$_2$edta)(*mono*ha)], shown in Scheme 1.

Of the red Ru^{III}-hydroxamato complexes synthesised, all but one yielded products of general formula [Ru(H$_2$edta)(*mono*ha)] (where *mono*ha = bha, 3- or 4-NH$_2$-pha, 2-, 3- or 4-Cl-pha, 2-, 3- or 4-Me-pha) and the % yields follow the substitution order 2- < 3- < 4-. Reaction of K[Ru(Hedta)Cl]·2H$_2$O with 2-NH$_2$-phaH failed to yield the desired product, [Ru(H$_2$edta)(2-NH$_2$-pha)], rather a blue solution resulted, which rapidly changed to brown, from which a brown solid was subsequently isolated and characterised as the Ru^{II}-nitrosyl, K[Ru(Hedta)(NO)Cl]. Blue Ru^{III}-edta-catecholamine complexes have previously been reported.[24] The *N*-methyl-substituted derivative, [Ru(H$_2$edta)(*N*-Me-bha)], obtained in high yield and high purity, is the first of its kind with Ru^{III} to be reported.

Dinuclear Ru^{III}-hydroxamato complexes

To date, there have been no reports in the literature on Ru^{III}-dihydroxamato complexes. A Ni^{II}(2,6-pyha) complex has been reported where the dihydroxamato ligand chelates the Ni^{II} ion

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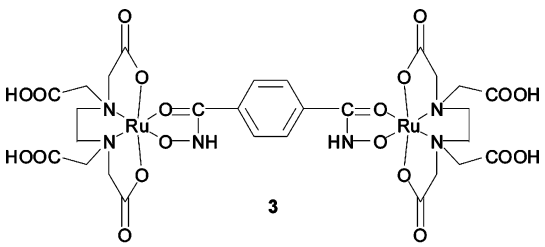
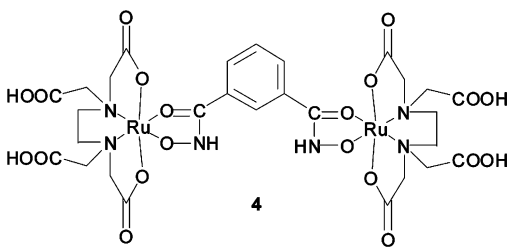
via the $\{N,N_{py},N\}$ donor set to give a discrete mononuclear $[PPh_4]_2[Ni(2,6\text{-pyha})_2]\cdot 7H_2O$ complex.[25] Another report describes the use of 1,3-benzodihydroxamic acid (L) in the construction of an Fe_4L_6 pyramid and consequently a three-dimensional porous metal–organic framework.[26] Herein, we report reaction of the dihydroxamic acids, 1,3-bhaH_2, 1,4-bhaH_2 and 2,6-pyhaH_2 with 2 equivalents of K[Ru(Hedta)Cl], which affords novel dinuclear Ru^{III}-dihydroxamato complexes $[\{Ru(H_2edta)\}_2(\mu\text{-}1,3\text{-bha})]$, $[\{Ru(H_2edta)\}_2(\mu\text{-}1,4\text{-bha})]$ and $[\{Ru(H_2edta)\}_2(\mu\text{-}2,6\text{-pyha})]$, respectively (Fig. 2), where the dihydroxamic acids coordinate in a bridging fashion *via* two independent *O*,*O′* donor head groups. Elemental analyses and ESI-MS for the dinuclear Ru^{III}-dihydroxamato complexes, together with the potentiometric study (discussed later) and a comparison of their IR spectra *versus* those of the free dihydroxamic acids, unambiguously confirm the formation of the bridging dihydroxamato complexes. In the IR spectrum of $[\{Ru(H_2edta)\}_2(\mu\text{-}1,4\text{-bha})]\cdot 2H_2O$, for example, a ν_{CO} at 1668 cm^{-1} and at 1724 cm^{-1} can be assigned to the stretching frequencies of the carbonyl groups of the glycinato and free glycine arms of edta, respectively. The ν_{CO} at 1609 cm^{-1} is that of the hydroxamato carbonyl groups and is approximately 40 cm^{-1} less than that observed in the spectrum of the free ligand, indicative of hydroxamato (*O*,*O′*) coordination.





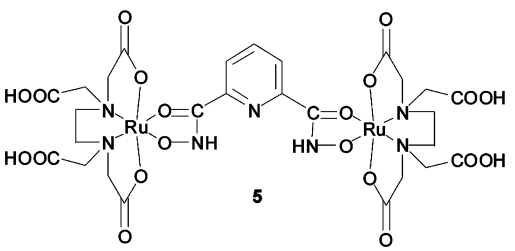


Fig. 2 Structures of $[\{Ru(H_2edta)\}_2(\mu\text{-}1,4\text{-bha})]$ **3**, $[\{Ru(H_2edta)\}_2(\mu\text{-}1,3\text{-bha})]$ **4** and $[\{Ru(H_2edta)\}_2(\mu\text{-}2,6\text{-pyha})]$ **5**.

ESI-MS in the negative mode was used to unequivocally identify the dinuclear Ru^{III}-dihydroxamato complexes; mass peaks at 977, 977 and 978 amu were observed for $[\{Ru(H_2edta)\}_2(\mu\text{-}1,3\text{-bha})]$ (978), $[\{Ru(H_2edta)\}_2(\mu\text{-}1,4\text{-bha})]$ (978) and $[\{Ru(H_2edta)\}_2(\mu\text{-}2,6\text{-pyha})]$ (979), and all of which display the characteristic Ru isotopic abundances. $[\{Ru(H_2edta)\}_2(\mu\text{-}1,4\text{-bha})]\cdot 2H_2O$ was also found to have a magnetic moment of 2.16 μ_B at room temperature, typical of a low-spin paramagnetic Ru^{III} complex and indicative of no magnetic exchange between the Ru^{III} centres at this temperature. In the IR spectra of both $[\{Ru(H_2edta)\}_2(\mu\text{-}1,3\text{-bha})]\cdot 4H_2O$ and $[\{Ru(H_2edta)\}_2(\mu\text{-}2,6\text{-pyha})]\cdot 4H_2O$, the ν_{CO} of the hydroxamato and edta glycinato arms are merged and appear as one broad band.

Formation constants and species-distribution curves

Speciation and spectroscopic studies were carried out on ligands L where L is 3- and 4-NH_2-phaH, 4-NMe_2-phaH, 2-, 3- and 4-Cl-phaH, 3-Me-phaH and their complexes with the binary Ru^{III}-edta system and the results support the presence of the ternary Ru^{III}-edta-hydroxamato complexes of general formula $[Ru(edta)(\textit{mono}ha)]^{2-}$, similar to those found in the solid state (**3**–**11** and **13**). The 2-Me-pha and 4-Me-pha systems were previously reported.[14]

The ternary Ru^{III}-edta-monohydroxamic acid systems

The pK_a values for the ligands synthesised, the details of which are given in Table 2, are as one would expect with 4-NMe_2-phaH having the highest pK_a value (9.47) and 2-Cl-phaH having the lowest (8.27). The stability constants of the aromatic hydroxamato complexes of general formula $[Ru(edta)(\textit{mono}ha)]^{2-}$ or ML, (where *mono*ha or L = bha or its monosubstituted derivatives 3-NH_2-pha, 4-NH_2-pha, 2-Cl-pha, 3-Cl-pha, 4-Cl-pha, 3-Me-pha and 4-NMe_2-pha), were obtained pH-metrically and lie in the range 6.15(4)–7.05(1), Table 2.

With the exception of the 4-*N*Me_2-pha derivative, $[Ru(edta)(NMe_2\text{-pha})]^{2-}$ (log β = 7.32(3)), all the complexes studied (in which the ratio of Ru^{III} : monohydroxamic acid ligand was 1 : 1), having log β values ranging from 6.15(4) to 7.05(1), are less stable than the previously reported benzohydroxamato Ru(edta) complex, $[Ru(edta)(bha)]^{2-}$ (log β = 7.28(1)),[14] despite the variance in basicity of ligands studied relative to the benzohydroxamato ligand. Interestingly also is the fact that, although the order of basicity of the amino derivatives is 4-NMe_2-phaH >2-NH_2-phaH >3-NH_2-phaH >4-NH_2-phaH, the order of complex stability is $[Ru(edta)(NMe_2\text{-pha})]^{2-}$ > $[Ru(edta)(4\text{-}NH_2\text{-pha})]^{2-}$ > $[Ru(edta)(3\text{-}NH_2\text{-pha})]^{2-}$. Species distribution and formation constants for the 2-NH_2-pha system were not obtained as 2-NH_2-phaH reacted quickly and irreversibly with the Ru(edta) system to form the nitrosyl adduct. Therefore competing nitrosyl formation hampered the speciation studies for ternary systems involving 2-NH_2-phaH. It is also noteworthy that *para*-substituted Ru(phenylhydroxamato) complexes were more stable than the corresponding *meta*-substituted phenylhydroxamato complexes, which were in turn more stable than the *ortho*-substituted derivatives despite the different electronic properties associated with the different substituents where the order of stability of the ML species was: 4-NMe_2-pha > bha > 4-NH_2-pha > 4-Cl-phaH > 3-Me-phaH > 3-NH_2-pha > 3-Cl-phaH > 2-Cl-pha, Table 2.

The titration curve for the ternary Ru-3-NH_2-phaH system, as a representative example, and typical of the Ru-*mono*hydroxamic

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Table 2 Protonation and overall stability constants (log β^a) and selected stepwise stability constants (log K^b) for complexes formed between K[Ru(Hedta)Cl]·2H$_2$O and hydroxamic acids, $I = 0.10$ M KNO_3 and $T = 25$ °C (standard deviations given in parentheses)

logβ	$M_pL_qH_r$	bhaH[14]	1,3-bhaH$_2$	2,6-pyhaH$_2$	3-NH$_2$-phaH	4-NH$_2$-phaH	4-NMe$_2$-phaH	2-Cl-phaH	3-Cl-phaH	4-Cl-phaH	3-Me-phaH
HL	011	8.66(1)	9.20(1)	9.09(1)	8.86(1)	8.74(1)	9.47(1)	8.27(2)	8.32(2)	8.44(1)	8.64(1)
H_2L	012		17.24(1)	16.90(1)	12.29(1)	11.62(1)					
H_3L	013			19.24(2)							
ML	110	7.28(1)			6.55(1)	7.05(1)	7.32(3)	6.15(4)	6.35(3)	6.72(3)	6.66(3)
MLH_{-1}	11-1				−0.64(1)	−0.39(2)	−0.18(4)	−0.21(4)	−0.16(3)	0.16(3)	−0.52(3)
MLH_{-2}	11-2				−11.39(5)	−10.54(3)	−10.77(8)	−10.76(9)	−10.70(9)	−10.42(9)	−11.27(9)
log K											
$ML \leftrightarrow MLH_{-1}$					−7.19	−7.44	−7.50	−6.36	−6.51	−6.88	−7.18
$MLH_{-1} \leftrightarrow MLH_{-1}(OH) + H^+$					−10.75	−10.15	−10.59	−10.55	−10.54	−10.26	10.75
M_2L	210		12.74(5)	12.30(6)							
M_2LH_{-1}	21-1		4.53(6)	4.54(7)							

[a] log β values refer to the equilibrium $pM + qL + rH \leftrightarrow M_pL_qH_r$. [b] log K values refer to the equilibrium $M_pL_qH_r \leftrightarrow M_pL_qH_{(r-1)}$.

acid systems studied, is shown in Fig. S1 (see ESI†) and is compared to those for the free ligand 3-NH_2-phaH and the binary $[Ru(Hedta)Cl]^-$. In the ternary system there are three dissociable protons below pH 10; the first two correspond to deprotonation of the Hedta ligand and the hydroxamic acid leading to $[Ru(edta)(3\text{-}NH_2\text{-}pha)]^{2-}$ and the third ionisation, in weakly alkaline solution, is due to deprotonation of the NH group of the coordinated hydroxamato giving the dianionic hydroximato complex $[Ru(edta)(3\text{-}NH_2\text{-}phaH_{-1})]^{3-}$.

The concentration-distribution curves for the ternary Ru-3-NH_2-phaH system, again described here as a representative example, are shown in Fig. 3 and Fig. 4. The yellow-coloured binary Ru(edta) complex reacts with 3-NH_2-phaH from *ca.* pH 3.3 to give the red $[Ru(edta)(3\text{-}NH_2\text{-}pha)]^{2-}$ complex, which is the dominant species between *ca.* pH 5.3–7.2. $[Ru(edta)(3\text{-}NH_2\text{-}pha)]^{2-}$ has a maximum concentration at pH 6.4 whereupon deprotonation of the hydroxamato NH group commences, resulting in the formation of the purple doubly deprotonated hydroximato complex $[Ru(edta)(3\text{-}NH_2\text{-}phaH_{-1})]^{3-}$, the major species in solution between *ca.* pH 7.0–10.0. Above *ca.* pH 7.5, the hydroxo complex $[Ru(edta)(3\text{-}NH_2\text{-}phaH_{-1})(OH)]^{4-}$ is observed.

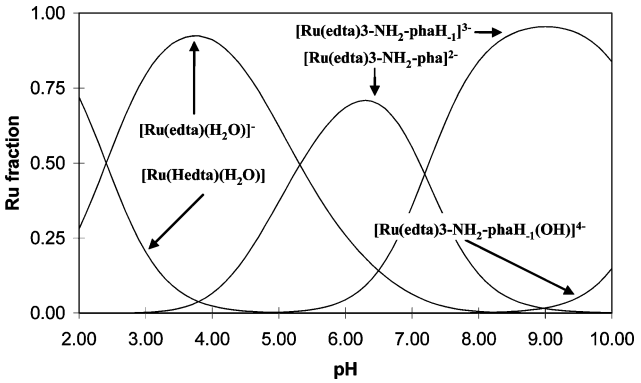

Fig. 3 Species distribution for Ru^{III}-3-NH_2-phaH, $[Ru^{III}] = 2$ mM, Ru^{III}–3-NH_2-phaH = 1 : 1.

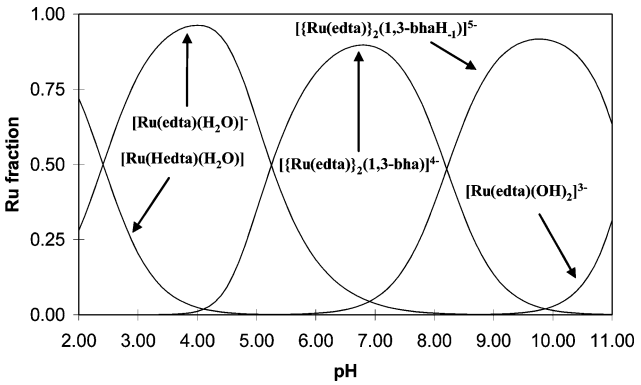

Fig. 4 Species distribution for Ru^{III}-1,3-bhaH$_2$, $[Ru^{III}] = 2$ mM, Ru^{III}–1,3-bhaH$_2$ = 2 : 1.

Although several examples involving hydroximato coordination have been cited in the literature, these mainly involve oligonuclear metallacrowns.[1] In addition to our previous report detailing the

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only examples of Ru^{III} hydroxamato and hydroximato complexes,[14] there are only a handful of reports on deprotonation of hydroxamato to hydroximato ligands in mononuclear complexes. Hydroximato complexes of Cu[27] and V[28] at high pH were identified by EPR spectroscopy and those of Mo by ^{17}O and ^{1}H NMR spectroscopy.[29] Benzo- and anthranilo-hydroximato manganate (IV and III respectively) complexes have also been reported.[30] A more recent report by Hambley and co-workers details an elegant study whereby, upon manipulation of pH, they were successful in isolating either the hydroxamato or hydroximato Co^{III}-tpa (tpa is tris(2-methylpyridyl)amine) complexes in the solid state including the mononuclear hydroximato complexes $[Co(achaH_{-1})tpa]ClO_4\cdot 0.5H_2O$, $[Co(pphaH_{-1})tpa](ClO_4)_{0.5}\cdot 4H_2O$ and $[Co(bhaH_{-1})tpa]Cl\cdot 6H_2O$ where $achaH_{-1}$, $pphaH_{-1}$ and $bhaH_{-1}$ are acetohydroximato, propionhydroximato and benzohydroximato, respectively, and the crystal structures of which they reported. They also report a crystal structure in which the asymmetric unit consists of two independent molecules, with one each of the hydroxamato, [Co(acha)(tpa)] and hydroximato, $[Co(achaH_{-1})(tpa)]$ forms of the acetohydroxamic acid ligand.[9]

The ternary Ru^{III}-edta-dihydroxamato systems

The pK_a values for the dihydroxamic acids, 1,3-$bhaH_2$ (8.04 and 9.20) and 2,6-$pyhaH_2$ (2.34, 7.81 and 9.09) were calculated, the former values of which have not previously been reported, Table 2.

The titration curve for the ternary Ru-1,3-$bhaH_2$ system, as a representative example, and typical of the dihydroxamic acids studied, is shown in Fig. S2 (see ESI†) and is compared to that of the free ligand 1,3-$bhaH_2$ and the binary $[Ru(Hedta)Cl]^-$. In these studies, there was a 4 : 1 excess of Ru^{III} to dihydroxamic acid used to ensure that all ligand present reacted with the Ru^{III}. Two deprotonation processes were observed for the ligand; upon titration with KOH, two protons are released, one from each of the hydroxamato OH groups, Table 2. Four dissociable protons are observed in the ternary Ru-edta-1,3-$bhaH_2$ system below pH 7, the first two of which correspond to deprotonation of the Hedta ligand followed by deprotonation of the two hydroxamato moieties of 1,3-$bhaH_2$ leading to the formation of $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bha)]^{4-}$, the major species present in solution between pH 5.2–8.2, Fig. 4. Under weakly alkaline conditions, deprotonation of one of the two NH's of the coordinated 1,3-bha is observed giving the novel triply deprotonated trianionic hydroximato complex $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bhaH_{-1})]^{5-}$.

The pK_a values for the Ru^{III} dihydroxamato complexes, $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bha)]^{4-}$ and $[\{Ru(edta)\}_2(\mu\text{-}2,6\text{-}pyha)]^{4-}$, corresponding to deprotonation of hydroxamato NH protons were found to be 8.21 and 7.76, respectively, Table 2. These values are higher compared to the Ru monohydroxamato complexes due to the increased overall negative charge of their conjugate acids *i.e.* 4- in the case of the dihydroxamato complexes, $[\{Ru(edta)\}_2(\mu\text{-}di\text{ha})]^{4-}$ compared to 2- for the monohydroxamato complexes, $[Ru(edta)(mono\text{ha})]^{2-}$. With the exception of $[\{Ru(edta)\}_2(\mu\text{-}1,4\text{-}bha)]^{4-}$ (which could not be investigated potentiometrically due to poor aqueous solubility although the complex $[\{Ru(H_2edta)\}_2(\mu\text{-}1,4\text{-}bha)]\cdot 4H_2O$ was isolated in the solid state) the stability constants of the dihydroxamato complexes of general formula $[\{Ru(edta)\}_2(\mu\text{-}di\text{ha})]^{4-}$ or M_2L were obtained pH-metrically. The $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bha)]^{4-}$ complex has a slightly higher log β value relative to the $[\{Ru(edta)\}_2(\mu\text{-}2,6\text{-}pyha)]^{4-}$ complex, Table 2.

The concentration distribution curves for the Ru-1,3-$bhaH_2$ system, again as a representative example, are shown in Fig. 4 and are the first of their kind to be reported in the literature. The yellow-coloured binary Ru(edta) complex reacts with 1,3-$bhaH_2$ from *ca.* pH 4 to give the reddish–brown $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bha)]^{4-}$ complex, which is the dominant species between *ca.* pH 5.2–8.2. This species has a maximum concentration at *ca.* pH 7 whereupon deprotonation of only one of the two hydroxamato NH groups commences. This results in the formation of $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bhaH_{-1})]^{5-}$, with one hydroxamic acid function coordinated to Ru^{III} *via* (*O*,*O*′) hydroxamato where the NH remains intact while the other is coordinated to the second Ru^{III} in the doubly deprotonated (*O*,*O*′) hydroximato form with deprotonated N. This is the major species in solution above *ca.* pH 8.2.

The formation of $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bhaH_{-1})]^{5-}$, where one of the two hydroxamato NH groups is deprotonated, was confirmed by a UV-VIS spectrophotometric study. As can be seen from Fig. 5, upon increasing pH from 7.5 to 9.3, the colour of the solution changes from red to purple and the LMCT band corresponding to the hydroxamato O–Ru^{III} transition shifts to longer wavelength due to the formation of the new hydroximato complex $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bhaH_{-1})]^{5-}$ and consistent with previously reported metal hydroxamato to hydroximato conversion. This shift was not observed for [Ru(edta)(*N*-Me-acha)]$^{2-}$, as previously reported, where such a deprotonation could not occur.[14] Beyond pH 8.5, there is no further shift in λ_{max}, indicative of the presence of only one species *i.e.* $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bhaH_{-1})]^{5-}$. The presence of this species was further supported by our speciation studies, Fig. 5.

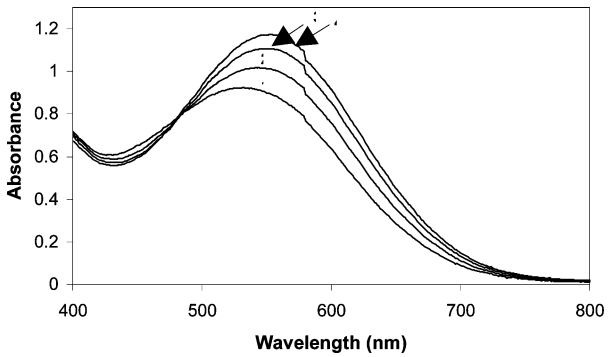

Fig. 5 UV-VIS spectra of $K[Ru^{III}(Hedta)Cl]\cdot 2H_2O$ + 1,3-$bhaH_2$, $[Ru^{III}] =$ 2 μM, [1,3-$bhaH_2$] = 1 mM, initial volume 5 mL, titrated with 0.5 M KOH; spectra 1: pH 7.5; spectra 2: 7.9; spectra 3: pH 8.5; spectra 4: 9.3. $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bha)]^{4-}$, $\lambda_{max} = 534$ nm; $[\{Ru(edta)\}_2(\mu\text{-}1,3\text{-}bhaH_{-1})]^{5-}$, $\lambda_{max} = 554$ nm.

Ru^{II}-nitrosyl complexes

Reaction of $K[Ru(Hedta)Cl]\cdot 2H_2O$ with achaH, bhaH, 2-, 3- or 4-NH_2-phaH, 2-, 3- or 4-Cl-phaH and 2-, 3- or 4-Me-phaH and 2,6-$pyhaH_2$ on heating, resulted in the facile formation of the brown Ru^{II}-nitrosyl adduct of formula K[Ru(Hedta)(NO)Cl] regardless of the hydroxamic acid used. Elemental analysis, IR, ^{1}H and ^{13}C NMR spectrum are consistent with the formulation $K[Ru^{II}(Hedta)(NO)Cl]\cdot H_2O$, and concur with previously reported

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examples of Ru^{II}-edta-NO complexes in the literature.[22] The IR spectra of K[Ru(Hedta)(NO)Cl]·H_2O contains a distinctive ν_{NO} at 1894 cm^{-1}. ESI-MS in the negative mode was used to unequivocally identify the Ru^{II}-NO complex, $[Ru^{II}(Hedta)(NO)Cl]^-$; a mass peak at 456 amu with the characteristic Ru isotopic abundance was observed. Interestingly, we found that the *N*-substituted hydroxamic acid, *N*-Me-bhaH, lacking the NH hydroxamato proton, regardless of the reaction conditions, did not release NO.

In contrast, 1,3- and 1,4-bhaH_2, when reacted with K[Ru(Hedta)Cl] under reflux, predominately gave the corresponding dinuclear Ru^{III}-dihydroxamato complexes and while the nitrosyl adduct could be isolated, it was obtained as the minor product.

Nitrosyl abstraction from hydroxamic acids

As previously reported by us, K[Ru(Hedta)Cl] abstracts NO from hydroxamic acids on heating to form the stable Ru^{II}-nitrosyl complex $K_2[Ru^{II}(edta)(NO)Cl]$ and the corresponding carboxylic acid. We proposed that this reaction involves initial formation of a $[Ru^{III}(edta)(hydroxamato)]^{2-}$ complex that undergoes nucleophilic attack by hydroxide on the hydroxamato carbonyl carbon, to give a tetrahedral intermediate from which hydroxylamine (a known source of NO) is eliminated with subsequent formation of the Ru^{II}-nitrosyl complex $[Ru^{II}(edta)(NO)Cl]^{2-}$. We found that the optimum pH for nitrosyl formation was at *ca.* pH 4.5. Above this pH, the Ru^{III} hydroximato complex (*via* deprotonation of the hydroxamato N) starts to form and, as previously reported by us, this species cannot release NO under these experimental conditions.[14] However, it is noteworthy that, under physiological conditions, hydroxamic acids have been shown to release NO *via* a NO-mediated Fe-haem containing guanylate cyclase pathway.[3]

UV-VIS spectroscopic investigation

We decided to carry out a UV-VIS spectroscopic investigation to determine the rate of NO release from the aliphatic acetohydroxamic acid, the aromatic benzohydroxamic acid and from substituted benzohydroxamic acids where the substituents were either electron-withdrawing (–Cl) or electron-releasing (–NH_2 and/or –Me). Of the hydroxamic acids reported in this paper, all but the chloro derivatives could be investigated for NO release. Whilst they were sufficiently soluble for speciation studies, this was not the case for our kinetic investigation where the required ratio of ligand to Ru^{III} was 10 : 1. In any case, the rate of NO release from a total of 6 hydroxamic acids was investigated.

We reacted K[Ru(Hedta)Cl] with achaH, bhaH, 3-NH_2-phaH and 3-Me-phaH in ten-fold excess at pH 4.50 and at 50 °C in acetic acid–sodium acetate buffer and followed the reaction by UV-VIS spectroscopy. The formation of the ternary complex $[Ru(edta)(\textit{mono}ha)]^{2-}$ is marked by a colour change from yellow to red and the appearance of a hydroxamato ligand to Ru^{III} charge-transfer band. As the reaction proceeds at this pH, this LMCT band diminishes with time with a marked colour change from red to brown indicative of conversion of the Ru^{III}-hydroxamato complex to the Ru^{II}-nitrosyl adduct, $[Ru^{II}(edta)(NO)Cl]^-$, Scheme 2, and consistent with our solid-state study. Because NO release from the Ru^{III}(edta)(3-NH_2-pha) complex proved fastest, we decided to further investigate the rate of NO release from the Ru^{III}(edta)(2-NH_2-pha) and Ru^{III}(edta)(4-NH_2-pha) complexes with a view to examining the effect of substituent position on the rate. A summary of the results is given in Table 3.

Table 3 k_{obs} and λ_{max} for $[Ru(edta)(\textit{mono}ha)]^{2-}$ where *mono*ha = 2-, 3-, 4-NH_2-pha, acha, bha and 3-Mepha

	λ_{max}/nm	k_{obs}/min^{-1}
$[Ru(edta)(2\text{-}NH_2\text{-}pha)]^{2-}$	525	0.1381
$[Ru(edta)(4\text{-}NH_2\text{-}pha)]^{2-}$	516	7.7×10^{-3}
$[Ru(edta)(3\text{-}NH_2\text{-}pha)]^{2-}$	485	7.2×10^{-3}
$[Ru(edta)(acha)]^{2-}$	455	2.3×10^{-3}
$[Ru(edta)(bha)]^{2-}$	481	1.6×10^{-3}
$[Ru(edta)(3\text{-}Me\text{-}pha)]^{2-}$	483	1.3×10^{-3}

The UV-VIS spectra corresponding to the Ru(edta)(3-NH_2-pha) system and described here as a representative example, Fig. 6, exhibits a decrease in the LMCT band at 485 nm with time and is indicative of conversion of $[Ru^{III}(edta)(3\text{-}NH_2\text{-}pha)]^{2-}$ to $[Ru^{II}(edta)(NO)Cl]^-$. Spectra were recorded at 15 min intervals until such time as there was no further spectral change *i.e.* at time $t = 435$ min in this case. A plot of $\ln(Abs_t - Abs_\infty)$ *versus* time gives a straight line with a $k_{obs} = 7.2 \times 10^{-3}$ min^{-1}, where k_{obs} represents a combination of k_{eq} and k shown in Scheme 2. Of the hydroxamic acids studied, the decrease in the LMCT band of [Ru(edta)(2-NH_2-pha)]$^{2-}$ was fastest with a $k_{obs} = 0.1381$ min^{-1}, most probably due to the presence of the amino group at the 2-position relative to the hydroxamato moiety, which can partake in hydrogen bonding thereby stabilising the proposed tetrahedral intermediate in the mechanism described earlier.

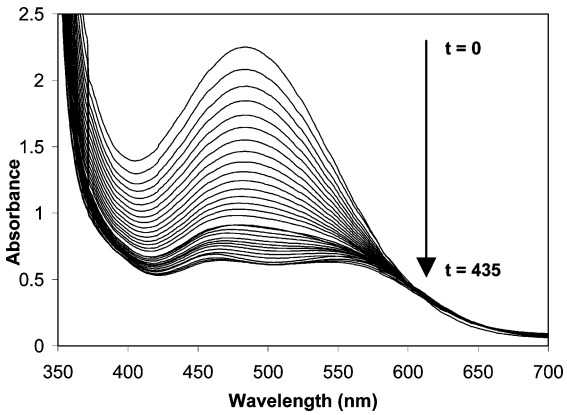
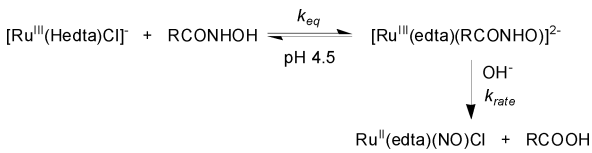


Fig. 6 UV-VIS spectra of the Ru(edta)-3-NH_2-phaH system where $[Ru^{III}] = 2$ mM and $[Ru^{III}]$–[3-NH_2-phaH] = 1 : 10. Spectra recorded at 15 min intervals, pH 4.50, 50 °C.



Scheme 2

Under the stated conditions, NO release from the Ru^{III}-acetohydroxamato complex is faster than that of the benzohydroxamato derivative, not surprising given the fact that the phenyl ring of the benzohydroxamato is electron withdrawing. The

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$[Ru(edta)(3\text{-}NH_2pha)]^{2-}$ complex releases NO over 5 times faster than the 3-Me-substituted derivative $[Ru(edta)(3\text{-}Mepha)]^{2-}$, suggesting that mesomeric in addition to inductive effects have a role to play.

Conclusions

In this paper we report the first examples of dinuclear Ru^{III} complexes with bridging dihydroxamato and dihydroximato ligands of general formula $[\{Ru(H_2edta)\}_2(\mu\text{-}di\text{ha})]$ and $[\{Ru(H_2edta)\}_2(\mu\text{-}di\text{ha}H_{-1})]^{-1}$, respectively. A series of mononuclear Ru^{III} hydroxamato and hydroximato complexes of general formula $[Ru(H_2edta)(mono\text{ha})]$ and $[Ru(H_2edta)(mono\text{ha}H_{-1})]^{-1}$, respectively, as well as the first example of a Ru^{III}-*N*-aryl aromatic hydroxamato derivative are reported. We also detail a UV-VIS spectroscopic investigation where we monitored the decrease in LMCT absorbance of a series of Ru^{III}-monohydroxamato complexes with time, gaining a better insight into the NO-releasing properties of aliphatic and aromatic hydroxamic acids.

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