Polyhedron 31 (2012) 524–529

Contents lists available at SciVerse ScienceDirect

Polyhedron

journal homepage: www.elsevier.com/locate/poly

Oxovanadium(V) complexes incorporating tridentate aroylhydrazoneoximes: Synthesis, characterizations and antibacterial activity

Subhashree P. Dash [a], Sagarika Pasayat [a], Saswati [a], Hirak R. Dash [b], Surajit Das [b], Ray J. Butcher [c], Rupam Dinda [a,*]

[a] Department of Chemistry, National Institute of Technology, Rourkela 769008, Orissa, India
[b] Department of Life Science, National Institute of Technology, Rourkela 769008, Orissa, India
[c] Department of Chemistry, Howard University, Washington, DC 20059, USA

ARTICLE INFO

Article history:
Received 24 June 2011
Accepted 5 October 2011
Available online 18 October 2011

Keywords:
Aroylhydrazoneoxime ligand
Oxovanadium(V) complexes
X-ray crystal structure
Antibacterial study

ABSTRACT

Some new oxovanadium(V) complexes, $[VOL^{1-3}(OEt)(EtOH)]$ (**1**–**3**), have been reported, which were obtained from the reaction of the Schiff bases H_2L^{1-3} (where H_2L^1 = the salicylhydrazone of diacetyl monoxime; H_2L^2 = the 4-methoxy salicylhydrazone of diacetyl monoxime and H_2L^3 = the 4-hydroxy salicylhydrazone of diacetyl monoxime) with $VO(acac)_2$ in a 1:1 molar ratio. Three 4-R-aroylhydrazoneoximes (**V**) have been used as ligands in the present study, differing in the inductive effect of the substituent R (R = H, OCH_3 and OH), in order to observe their influence, if any, on the redox potentials and biological activity of the complexes. All the synthesized ligands and metal complexes were successfully characterized by elemental analysis, IR, UV–Vis and NMR spectroscopy. An X-ray diffraction study of $[VOL^1(OEt)(EtOH)]$ (**1**) reveals that the metal center has a distorted octahedral O_5N coordination sphere, where the O,N,O donor ligand and the ethoxo group constitute a satisfactory O_3N basal plane. Cyclic voltammetry of the complexes show a quasi-reversible cyclic voltammetric response in the potential range 0.29–0.36 V involving a single electron V(V)–V(IV) reduction. The complexes have also been screened for their antibacterial activity against *Escherichia coli*, *Bacillus, Proteus* and *Klebsiella*. Minimum inhibitory concentrations of these complexes and the antibacterial activities indicate compound **1** as the potential lead molecule for drug design.

1. Introduction

The chemistry of vanadium has become a fascinating area of research in recent time because of the presence of vanadium in metalloenzymes and its medicinal as well as catalytic importance [1–13]. The expanding knowledge of the role of vanadium in biological systems as a therapeutic agent, for example in antitumor and anticancer drugs [14,15], has led to a continuously increasing interest in the coordination chemistry and solution chemistry of this element.

Over the years, oximes have been widely used as very efficient complexing agents in analytical chemistry for the isolation, separation and extraction of different metal ions [16–26]. Metal complexes of oxime also have various interesting features [27,28], which include short intramolecular hydrogen bonding and packing configurations that give rise to unusual optical properties. From a medicinal chemistry point of view, it is found that they serve as models for biosystems such as vitamin B_{12} [29] and myocardial perfusion imaging agents [30]. As a ligand, the oxime moiety is potentially ambidentate [16] and can coordinate either through the nitrogen (**I**, Chart 1) [23–26] or the oxygen atom (**II**) [31]. The vast literature on structural studies of oxime complexes reveals some interesting features of its coordination behavior. It may coordinate to one metal ion through the nitrogen atom and another metal ion through the oxygen atom (**III**). Thus it can form a $\mu_{1,2}$ (N,O) oximato-bridged extended network [19–22]. In the majority of complexes, only the nitrogen atom (**I**) coordinates to the metal center, and the oxygen atom does not take part in coordination, although there are quite few examples where both the atoms (oximato nitrogen and oxygen, **IV**) do take part in coordination [32,33].

On the other hand, hydrazones –NH–N=CRR' (R and R′ = H, alkyl, aryl) are versatile ligands due to their applications in the field of analytical [34] and medicinal chemistry [35]. Hydrazone moieties are the most important pharmacophoric cores of several anti-inflammatory, antinociceptive and antiplatelet drugs [36]. It may be relevant to mention here that although the chemistry of aroylhydrazones complexes of many transition metals has been extensively studied [37–40], that of aroylhydrazoneoximes (**V**) appears to have remained practically unexplored [41,42].

* Corresponding author. Tel.: +91 661 246 2657; fax: +91 661 246 2022.
E-mail address: rupamdinda@nitrkl.ac.in (R. Dinda).

0277-5387/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.poly.2011.10.017

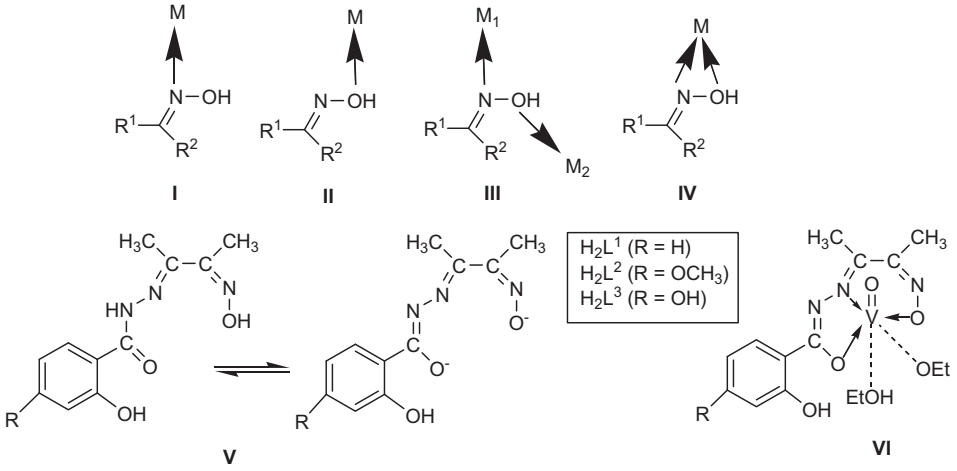

Chart 1. Structures **I–VI**.

Keeping this observation in mind and in continuation of our studies on oxovanadium complexes of hydrazone Schiff base ligands [43–44], the oxime functionality is incorporated into the ligand moiety. In this paper we report the syntheses, X-ray structure and physical properties of some oxovanadium(V) complexes of aroylhydrazoneoximes, with special reference to their antibacterial activity. It is worth mentioning here that, to the best of our knowledge, this report is a rare example [31] of aroylhydrazoneoxime complexes where the oximato oxygen atom coordinates to the metal center, while the nitrogen atom does not take part in coordination.

2. Experimental

2.1. Materials

$[VO(acac)_2]$ was prepared as described in the literature [45]. Reagent grade solvents were dried and distilled prior to use. All other chemicals were reagent grade, available commercially and used as received. Commercially available TBAP (tetra butyl ammonium perchlorate) was properly dried and used as a supporting electrolyte for recording the cyclic voltammograms of the complexes.

2.2. Physical measurements

Elemental analyses were performed on a Vario ELcube CHNS Elemental analyzer. IR spectra were recorded on a Perkin-Elmer Spectrum RXI spectrometer. ^{1}H NMR spectra were recorded with a Bruker Ultrashield 400 MHz spectrometer using $SiMe_4$ as an internal standard. Electronic spectra were recorded on a Lamda25, Perkin-Elmer spectrophotometer. Magnetic susceptibility was measured with a Sherwood Scientific AUTOMSB sample magnetometer. Electrochemical data were collected using a PAR electrochemical analyzer and a PC-controlled Potentiostat/Galvanostat (PAR 273A) at 298 K in a dry nitrogen atmosphere. Cyclic voltammetry experiments were carried out with a glassy carbon working electrode, platinum counter electrode and Ag/AgCl as reference electrode, and TBAP as the supporting electrolyte. Antibacterial activity was measured with a Perkin-Elmer (2030 VICTOR X_3) microtitre plate optical colorimeter (OD_{600}).

2.3. Synthesis of the ligands (H_2L^1, H_2L^2, H_2L^3)

The Schiff base ligands H_2L^{1-3} were prepared in 80–90% yield by the condensation of an equimolar ratio of 4-substituted salicylhydrazine with diacetyl monoxime in methanol media by standard procedures [46]. The resulting white compound was filtered, washed thoroughly with ethanol and dried over fused $CaCl_2$.

2.4. Synthesis of the complexes $[VO(L^{1-3})(OEt)(EtOH)]$ (**1**–**3**)

To a stirring solution of the ligand H_2L^{1-3} (1.0 mmol) in 20 mL of ethanol, $VO(acac)_2$ (1.0 mmol) was added. The color changed to brownish red. After 3 h of stirring, the solution was filtered. The filtrate was allowed to stand at room temperature for 4 days, during which crystals, suitable for X-ray analysis, were isolated. *[VO(L^1)(OEt)(EtOH)]* (***1***)*:* Yield: 58%. *Anal.* Calc. for $C_{15}H_{22}N_3O_6V$: C, 46.03; H, 5.62; N, 10.74. Found: C, 46.07; H, 5.65; N, 10.79%. ^{1}H NMR (DMSO-d_6, δ): 2.63 (s, 3H, $CH_3C{=}NN$), 2.52 (s, 3H, $CH_3C{=}NO$), 7.86–6.93 (m, 4H, C_6H_4), 11.42 (s, 1H, OH). ^{51}V NMR (DMSO-d_6, δ): −513. *[VO(L^2)(OEt)(EtOH)]* (***2***)*:* Yield: 54%. *Anal.* Calc. for $C_{16}H_{24}N_3O_7V$: C, 45.60; H, 5.70; N, 9.97. Found: C, 45.65; H, 5.73; N, 9.94%. ^{1}H NMR (DMSO-d_6, δ): 2.68 (s, 3H, $CH_3C{=}NN$), 2.53 (s, 3H, $CH_3C{=}NO$), 3.71 (s, 3H, CH_3O), 7.94–6.83 (m, 3H, C_6H_4), 11.46 (s, 1H, OH). ^{51}V NMR (DMSO-d_6, δ): −518. *[VO(L^3)(OEt)(EtOH)]* (***3***)*:* Yield: 61%. *Anal.* Calc. for $C_{15}H_{22}N_3O_7V$: C, 44.22; H, 5.40; N, 10.31. Found: C, 44.27; H, 5.36; N, 10.27%. ^{1}H NMR (DMSO-d_6, δ): 2.61 (s, 3H, $CH_3C{=}NN$), 2.48 (s, 3H, $CH_3C{=}NO$), 7.74–6.87 (m, 3H, C_6H_4), 9.76 (s, 1H, *p*-Ar–OH), 11.48 (s, 1H, *o*-Ar–OH). ^{51}V NMR (DMSO-d_6, δ): −529.

2.5. Crystallography

A suitable single crystal of **1** was chosen for the X-ray diffraction studies. This compound crystallized in the monoclinic space group $P\ 121/n1$. The diffraction data for **1** were collected at 295 K with a Bruker AXS Smart CCD diffractometer using graphite monochromated Mo Kα radiation ($\lambda = 0.71073$ Å). The following Bruker software packages were used: SMART for collecting frames of data, indexing and determination of lattice parameters, SAINT for integration of intensity of reflections and scaling, SADABS for absorption correction, and SHELXTL for space group and structure determination, and for refinement. The structures were solved by direct methods with SHELX-86 and refined by full-matrix least-squares analysis with SHELXL-97 [47]. All the hydrogen atoms were added in their calculated positions using riding models, whereas non-hydrogen atoms were refined with anisotropic thermal parameters. Crystallographic data and details of refinement are given in Table 1.

Table 1
Crystallographic data and details of refinement for [VO(L^1)(OEt)(EtOH)] (**1**).

Identification code	rd-sd4
Empirical formula	$C_{15}H_{22}N_3O_6V$
Formula weight	391.30
T (K)	295(2)
λ (Å)	1.54184
Crystal system	monoclinic
Space group	$P121/n1$
Unit cell dimensions	
a (Å)	7.06518(10)
b (Å)	21.9429(3)
c (Å)	11.80060(13)
α (°)	90
β (°)	96.5499(12)
γ (°)	90
V (Å^3)	1817.51(4)
Z	4
D_{calc} (mg/m^3)	1.430
Absorption coefficient (mm^{-1})	4.887
F(000)	816
Crystal size (mm^3)	0.54 × 0.24 × 0.17
Theta range for data collection (°)	5.52–77.38
Index ranges	$-8 \leqslant h \leqslant 8$, $-27 \leqslant k \leqslant 26$, $-14 \leqslant l \leqslant 10$
Reflections collected	8227
Independent reflections (R_{int})	3776 (0.0201)
Completeness to theta = 67.50°	99.6%
Absorption correction	semi-empirical from equivalents
Maximum and minimum transmission	1.00000 and 0.19723
Refinement method	Full-matrix least-squares on F^2
Data/restraints/parameters	3776/10/250
Goodness-of-fit on F^2	1.042
Final R indices [$I > 2\sigma(I)$]	$R_1 = 0.0541$, $wR_2 = 0.1500$
R indices (all data)	$R_1 = 0.0604$, $wR_2 = 0.1563$
Largest difference in peak and hole (eÅ^{-3})	0.535 and −0.399

2.6. Antibacterial activity

The antibacterial activity of the compounds (ligands and complexes) was studied against *Escherichia coli* (*E. coli*), *Bacillus*, *Proteus* and *Klebsiella* by determining the minimum inhibitory concentration (MIC) values, following CLSI guidelines for the broth microdilution method [48]. Briefly, bacterial strains were cultured onto Luria Bertani Agar medium [containing 0.5% peptone, 0.5% yeast extract, 1% NaCl and 1.5% Agar, at pH 7.5 ± 0.2]. The stock solution was prepared by dissolving the tested compounds in dimethyl sulfoxide (DMSO). Chloramphenicol, a common antibiotic, was used as the positive control and DMSO was used as the negative control. Bacterial cultures were added to the sterilized Mueller Hinton Broth (MHB) [containing 30% beef extract, 1.75% casein acid hydrolysate and 0.15% starch, pH 7.4 ± 0.2]. The MIC was determined by using 2-fold serial dilutions in the medium (MHB) containing 1.95–1000 μg/ml of the test compounds. To each well of a 96 well microtitre plate, 150 μl of medium (MHB) was taken in duplicate, to which 10 μl of 0.5 McFarland standard (1.5×10^8 CFU/ml) culture pathogens from MHB was added. The inoculated plates were incubated at 37 °C for 24 h. After incubation, the bacterial growth was monitored by measuring the turbidity of the culture by a microtitre plate optical colorimeter (OD_{600}). The MIC was determined as the lowest concentration of compound at which the visible growth of the organisms was completely inhibited.

3. Results and discussion

3.1. Synthesis

Three 4-R-aroylhydrazoneoximes (**V**) have been used in the present study, differing in the inductive effect of the substituent R (R = H, OCH_3 and OH), in order to observe their influence, if any, on the redox potentials and biological activities of the complexes. The reactions of the selected aroylhydrazoneoximes (**V**) with $VO(acac)_2$ proceeded in stirring ethanol and each of these reactions afforded reddish black colored products in decent yields. During this reaction, vanadium is oxidized from its initial +IV state to the +V state. These compounds are highly soluble in aprotic solvents, viz. CH_3CN, DMF or DMSO.

3.2. Spectral characteristics

The spectral characteristics of **1**–**3** are listed in Table 2. The infrared spectra of the complexes display a broad band centered at around 3400 cm^{-1}. This band is possibly due to the O–H stretch of the hydrazine fragment of the ligand. The C=O stretch (1654 cm^{-1}) of the amide functionality [49] in the free ligand is found to be absent in the spectra of the complexes, which indicates that the Schiff base is completely deprotonated and acts as a dibasic enolate. The strong and sharp peak displayed by the complexes in the range 1592–1603 cm^{-1} is likely to be associated with the C=N–N=C moiety [43,44,50]. The presence of a strong band in the range 976–985 cm^{-1} is assigned to V=O stretching [43,44].

The electronic spectra of the complexes were recorded using acetonitrile solutions. The main features of all the spectra are quite similar. Three strong absorptions are observed in the wavelength range 403–207 nm. The lower energy absorption at around 390 nm is ascribable to ligand-to-metal charge transfer transitions, whereas the higher energy absorptions are likely to be due to ligand centered transitions [43,44].

The ^{1}H NMR spectral data of the free ligands and the corresponding oxovanadium(V) complexes (**1**–**3**) were recorded using DMSO-d_6. The spectra of the free ligands exhibit two close but separate singlets in the range 11.74–11.53 ppm due to NH and OH (=N–OH) groups, which are absent in the spectra of the complexes indicating coordination of these groups to the metal center. However all the spectra display a singlet in the range 11.42–11.48 ppm, which corresponds to the OH (phenolic) group of the ligand fragment, showing it remains uncoordinated in the complexes. Signals for the aromatic protons are found as multiplets in the 7.94–6.83 ppm range [46]. The protons of the methyl group of the methoxy substituent in [VO(L^2)(OEt)(EtOH)] (**2**) resonate as a singlet at 3.71 ppm and the proton of the hydroxyl substituent at the 4-position in [VO(L^3)(OEt)(EtOH)] (**3**) resonates as a singlet at 9.76 ppm [51]. The two methyl groups of the diacetyl monoxime moiety appear as singlets in the range 2.48–2.68 ppm. The ^{51}V NMR spectra of **1**–**3** display a singlet at −513, −518 and −529 ppm, respectively. These chemical shifts are usual for complexes containing the mono-oxovanadium(V) unit [52].

3.3. Electrochemical properties

The electrochemical properties of all the oxovanadium(V) complexes have been examined in CH_3CN solution (0.1 M TBAP) by cyclic voltammetry. All the complexes show a quasi-reversible cyclic voltammetric response in the potential range 0.29–0.36 V involving single electron V(V)–V(IV) reduction [44]. The one-electron nature of this reduction has been tentatively established by comparing its current height with that of the standard ferrocene/ferrocenium couple under the same experimental conditions. The potential data of **1**–**3** are listed in Table 3, and a selected voltammogram is shown in Fig. 1. The potential of the V(V)–V(IV) reduction in the 4-R-aroylhydrazoneoxime complexes (**VI**) has been found to be sensitive to the nature of the substituent R in the aroylhydrazone fragment. The potential decreases with increasing electron-releasing character of the substituent R, as expected [53,54].

Table 2
Characteristics IR[a] bands (cm^{-1}) and electronic spectral[b] data [nm (dm^3 mol^{-1} cm^{-1})] for complexes **1**–**3**.

Complex	ν(OH)	ν(C=N)	ν(V=O)	λ_{max} (ε)
[VO(L^1)(OEt)(EtOH)] (**1**)	3434	1592	977	383 (4324); 263 (11190); 221 (14423)
[VO(L^2)(OEt)(EtOH)] (**2**)	3381	1603	985	395 (5212); 278 (13654); 216 (15709)
[VO(L^3)(OEt)(EtOH)] (**3**)	3402	1598	976	403 (4931); 265 (12654); 207 (17809)

[a] KBr pellet.
[b] In CH_3CN.

Table 3
Cyclic voltammetric results[a] for oxovanadium(V) complexes **1**–**3** at 298 K.

Complex	$E_{1/2}$ (V)	ΔE_P (mV)
[VO(L^1)(OEt)(EtOH)] (**1**)	0.36	91
[VO(L^2)(OEt)(EtOH)] (**2**)	0.31	86
[VO(L^3)(OEt)(EtOH)] (**3**)	0.29	79

[a] In acetonitrile at a scan rate of 50 mV s^{-1}. $E_{1/2} = (E_{pa} + E_{pc})/2$, where E_{pa} and E_{pc} are the anodic and cathodic peak potentials vs. Ag/AgCl, respectively. $\Delta E_P = E_{pa} - E_{pc}$.

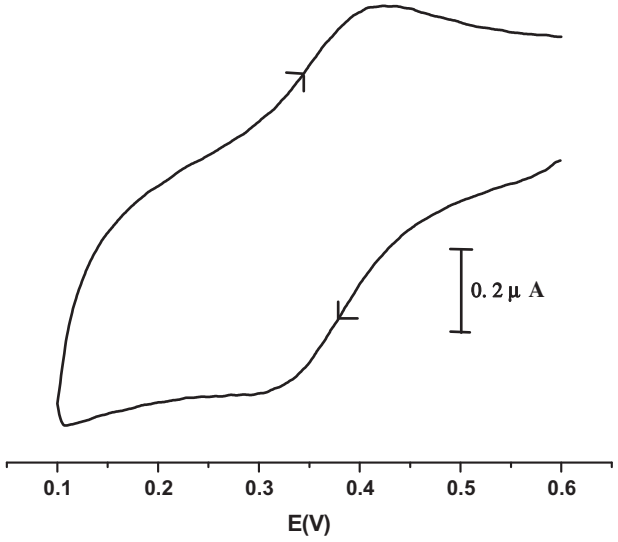

Fig. 1. Cyclic voltammogram of complex **1** in CH_3CN (0.1 M TBAP); scan rate 50 mV/s, and potentials recorded vs. Ag/AgCl.

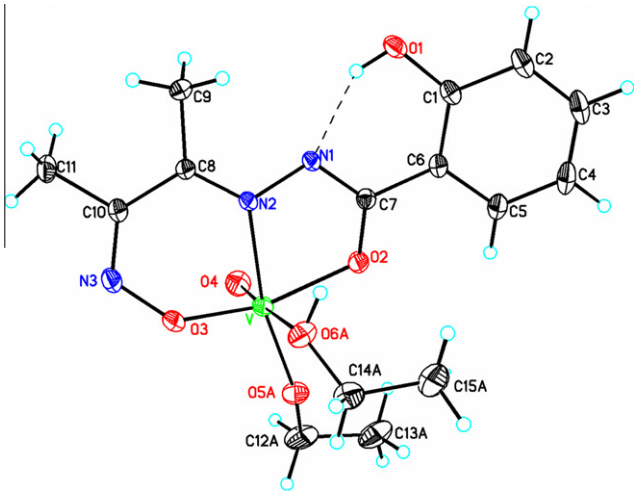

Fig. 2. ORTEP diagram of [VO(L^1)(OEt)(EtOH)], **1** with the atom labeling scheme.

Table 4
Selected bond distances (Å) and angles (°) for [VO(L^1)(OEt)(EtOH)] (**1**). The estimated standard deviations are shown in parentheses.

V–O(4)	1.580(3)	V–O(2)	1.984(2)
V–O(5A)	1.774(2)	V–N(2)	2.116(2)
V–O(3)	1.839(2)	V–O(6A)	2.366(2)
O(3)–V–N(2)	81.08(8)	N(2)–V–O(6A)	81.43(9)
O(3)–V–O(2)	149.44(9)	O(2)–V–O(5A)	94.02(10)
O(3)–V–O(5A)	103.71(11)	O(2)–V–O(4)	99.68(12)
O(3)–V–O(4)	100.03(13)	O(2)–V–O(6A)	79.30(10)
O(3)–V–O(6A)	79.20(11)	O(5A)–V–O(3)	103.71(11)
N(2)–V–O(2)	4.44(8)	O(5A)–V–O(6A)	80.86(11)
N(2)–V–O(5A)	160.40(10)	O(4)–V–O(6A)	175.46(11)
N(2)–V–O(4)	94.04(10)	O(4)–V–O(5A)	103.64(12)

*3.4. Description of the crystal structure of [VO(L^1)(OEt)(EtOH)] (**1**)*

Although the preliminary characterization data (microanalytical and spectroscopic) of the complexes gave some idea about their composition and the donor points through which the ligands were attached to the oxovanadium(V) center, they could not definitely reveal the actual structures, which could only be provided by a structure determination using the single-crystal X-ray diffraction technique. To determine the coordination mode of the aroylhydrazoneoxime ligands in these complexes (**1**–**3**), the structure of a representative member of this family, viz. [VO(L^1)(OEt)(EtOH)] (**1**), was determined. The molecular structure of **1** is shown in Fig. 2 and some relevant bond parameters are listed in Table 4. In the structure the metal center is in a distorted octahedral O_5N coordination sphere. The O,N,O donor ligand and the ethoxo group constitute a satisfactory O_3N basal plane, and the oxo group occupies an apical position. Essentially the same arrangement around vanadium has been seen in related systems [31,44,54]. The displacement of the metal center from the basal plane toward the apical oxo group is 0.2570(5) Å, though this displacement is noticeably small. This small displacement is possibly due to the coordination of the ethanol molecule [54]. The short V–O(4) distance of 1.580(3) Å indicates the presence of a vanadium–oxygen double-bond (V=O), which is commonly found in five- and six-coordinated octahedral complexes of vanadium(IV) and vanadium(V) [43,44,54–57]. The five V–O bond lengths are unequal; the V=O bond being the shortest and the V–O [ethanolic oxygen O(6A)] being the longest due to the trans influence of the oxo atom. The V–O bond lengths follow the order V–O (oxo) < V–O (ethoxide) < V–O (oxime) < V–O (enolate) < V–O (ethanolic). This data indicates stronger binding of the alkoxo group compared to the other bonded oxygen atoms. The V–O bond distance (av. 1.908 Å) is similar to those reported for V–O bonds in somewhat related systems [54]. The cis bond angles are in the range 74.44(8)–103.71(11)°, while the trans O=V–O (ethanol) bond angle of 175.46(11)° is almost linear as compared to the other two trans angles (149.44(9)° and 160.40(10)°) (Table 4). The orientation of the ethoxo ethyl in complex **1** is towards the oxo group side, perhaps due to steric constraints imposed by the metal coordinated ethanol, Fig. 2.

The one-dimensional self-assembling of the molecule [VO(L^1)(OEt)(EtOH)] is shown in Fig. 3. The molecule is found to show

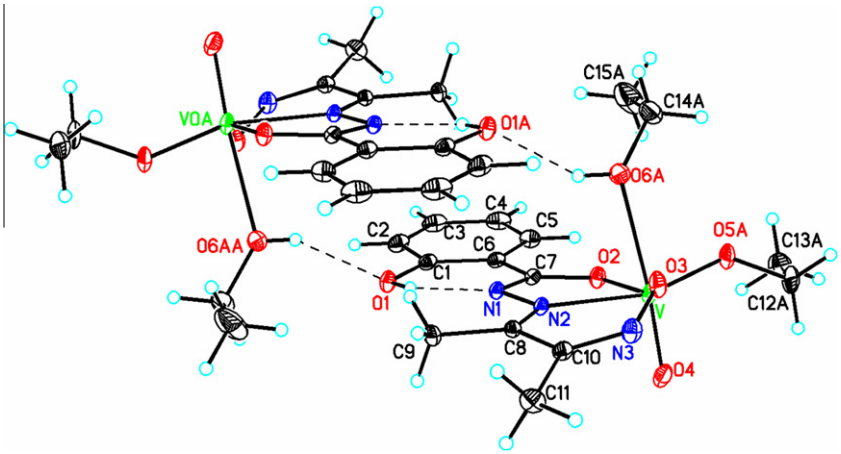

Fig. 3. Hydrogen bonding diagram of complex **1** with the atom labeling scheme.

Table 5
Hydrogen bond distances (Å) and angles (°) for [VO(L^1)(OEt)(EtOH)] (**1**).

D–H...A	*d*(D–H)	*d*(H...A)	*d*(D...A)	∠(DHA)
O(1)–H(1)...N(1)	0.82	1.84	2.562(3)	146.3
O(6A)–H(6A)...O(1)#1	0.82	2.35	2.847(3)	119.8

both inter and intra molecular hydrogen bonding. Two [VO(L^1)(OEt)(EtOH)] molecules form a dimeric unit via a pair of reciprocal hydrogen bonds between the phenolic oxygen of one molecule with the ethanolic proton of the other moiety, forming intermolecular hydrogen bonding. Another hydrogen bonding between N(1) and the phenolic hydrogen, H(1), is also observed, constituting an intramolecular hydrogen bond. The H-bonding parameters are listed in Table 5.

Structural characterization of complexes **2** and **3** by X-ray crystallography has not been possible, as their single crystals could not be grown. As all three complexes have been synthesized similarly and display similar properties, the other two [VO(L^{2-3})(OEt)(EtOH)] complexes (**2**–**3**) are assumed to have the same structure as [VO(L^1)(OEt)(EtOH)] (**1**). The results of the ^{1}H NMR in DMSO-δ_6 and IR in CH_2Cl_2 solution indicate that the structures of complexes **1**–**3** in solution remain the same as those in the solid state.

3.5. Antimicrobial activity

In the present study, the synthesized compounds (**1**–**3**) showed potential antibacterial activity against all the pathogens tested (*E. coli*, *Bacillus*, *Proteus* and *Klebsiella*), and in some cases they showed more promising results by giving MIC values that are lower than the standard drug examined. The biological data (Table 6) of the MIC of the free ligands showed poor activity (MIC = ~15.62–500 μg/mL), which is in agreement with the previous results (62.5–250 μg/mL) as reported by Sharma et al. [58] following the broth micro-dilution method. However, the corresponding oxovanadium(V) complexes (**1**–**3**) showed much better results with respect to the individual ligands. A possible explanation is that by coordination, the polarity of the ligand and the central metal ion are reduced through the charge equilibration, which favors permeation of the complexes through the lipid layer of the bacterial cell membrane [59,60]. Complex **1** showed the most promising results as compared to the other compounds (**2** and **3**) of this study and similar compounds against the same and other pathogens, as reported by Sharma et al. [58]. The antibacterial activity of similar type compounds has also been reported by Chohan et al. [61] and Tahira et al. [62] using the agar well diffusion technique against *E. coli*, *Shigella*, *Pseudomonas*, *Salmonella*, *Staphylococcus* and *Bacillus*, and the present results are in accordance with the reported values. However, the difference in value may be attributed to the nature of the compounds synthesized with different ligands.

Table 6
Antibacterial activity of all the ligands and oxovanadium(V) complexes, *in vitro* MIC in μg mL^{-1}.

	E. coli	*Bacillus*	*Proteus*	*Klebsiella*
H_2L^1	15.62	31.25	–	–
H_2L^2	125	–	125	500
H_2L^3	125	–	–	125
[VO(L^1)(OEt)(EtOH)] (**1**)	7.81	15.62	15.62	7.81
[VO(L^2)(OEt)(EtOH)] (**2**)	62.50	62.50	31.25	125
[VO(L^3)(OEt)(EtOH)] (**3**)	62.50	31.25	125	62.50
Chloramphenicol	2.00	2.00	16.00	16.00

Vanadium is a trace element which is essential for higher organisms for their survival, whereas vanadium(V) complexes are known as potential inhibitors of various enzymes [63]. There are reports of vanadium complexes showing antibacterial, antifungal and anticancerous properties [58,61–63]. Hence, the currently synthesized compounds have the potential to be used as an antimicrobial as well as an antidiabetic drug. There are also certain drawbacks in using vanadium complexes as a therapeutic agent as its toxicity varies with the route of administration and duration; however, there is no report yet available about its chronic toxicity [64].

4. Conclusion

The present study shows that the 4-R-aroylhydrazoneoximes ligands (H_2L^{1-3}, **V**) can bind to vanadium upon reaction with [VO(acac)$_2$], affording complexes of the type [VO(L)(OEt)(EtOH)], where the oxime oxygen atom coordinates to the metal center and the nitrogen atom does not take part in coordination (**VI**). All the complexes have been characterized with the help of various spectroscopic techniques and electrochemical measurements. X-ray diffraction measurements of **1**, [VO(L^1)(OEt)(EtOH)], have been carried out. The complexes **1**–**3** have also been screened for their antibacterial activity against *E. coli*, *Bacillus*, *Proteus* and *Klebsiella*. The minimum inhibitory concentration of these complexes and their antibacterial activity indicates compound **1** as the potential lead molecule for drug design.

Acknowledgements

The authors thank the reviewers for their comments and suggestions, which were helpful in preparing the revised version of the manuscript. The authors thank Dr. S.K. Chattopadhyay, Bengal Engineering and Science University, Shibpur for fruitful discussions. R.D. thanks Department of Science and Technology, Govt. of India for funds (Grant SR/FT/CS-016/2008) as SERC Fast Track Scheme of Young Scientist.

Appendix A. Supplementary data

CCDC 822842 contains the supplementary crystallographic data for complex **1**. These data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html, or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or e-mail: deposit@ccdc.cam.ac.uk.

References

[1] A. Butler, C.J. Carrano, Coord. Chem. Rev. 109 (1991) 61.
[2] H.F. Nielsen, E.O. Othus, in: N.D. Chasteen (Ed.), Vanadium in Biological Systems, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1990, pp. 51–62.
[3] D.W. Boyd, K. Kustin, Adv. Inorg. Biochem. 6 (1984) 311.
[4] H. Kneifel, E. Bayer, Angew. Chem., Int. Ed. Engl. 85 (1973) 542.
[5] H. Vilter, Phytochemistry 23 (1984) 1387.
[6] A. Butler, J.V. Walker, Chem. Rev. 93 (1993) 1937.
[7] M. Weyand, H.J. Hecht, M. Kieβ, M.F. Liaud, H. Vilter, D. Schomburg, J. Mol. Biol. 293 (1999) 595.
[8] D. Rehder, G. Santoni, G.M. Licini, C. Schulzke, B. Meier, Coord. Chem. Rev. 237 (2003) 53.
[9] C. Tsiamis, B. Voulgaropoulos, D. Charistos, G.P. Voutsas, C.A. Kavounis, Polyhedron 19 (2000) 2003.
[10] D.C. Crans, C.M. Simone, J.S. Blanchard, J. Am. Chem. Soc. 114 (1992) 4926.
[11] H. Sigel, A. Sigel (Eds.), Metal Ions in Biological Systems, Vanadium and its Role in Life, vol. 31, Marcel Dekker, New York, 1995. 779p.
[12] S. Macedo-Ribeiro, W. Hemrika, R. Renirie, R. Wever, A. Messerschmidt, J. Biol. Inorg. Chem. 4 (1999) 209.
[13] C. Slebodnick, B.J. Hamestra, V.L. Pecoraro, Struct. Bond. (Berlin) 89 (1997) 51.
[14] A.E. Evangelou, Crit. Rev. Oncol. Hematol. 42 (2002) 249.
[15] P. Köpf-Maier, Eur. J. Clin. Pharmacol. 47 (1994) 1.
[16] A. Chakravorty, Coord. Chem. Rev. 13 (1974) 1.
[17] S. Chattopadhyay, M.S. Ray, S. Chaudhuri, G. Mukhopadhyay, G. Bocelli, A. Cantoni, A. Ghosh, Inorg. Chim. Acta 359 (2006) 1367.
[18] M.S. Ray, A. Ghosh, R. Bhattacharya, G. Mukhopadhyay, M.G.B. Drew, J. Ribas, J. Chem. Soc., Dalton Trans. (2004) 252.
[19] S. Sreerama, S. Pal, Inorg. Chem. 41 (2002) 4843.
[20] D. Datta, A. Chakravorty, Inorg. Chem. 21 (1982) 363.
[21] S. Ross, T. Weyhermüller, E. Bill, E. Bothe, U. Flörke, K. Wieghardt, P. Chaudhuri, Eur. J. Inorg. Chem. (2004) 984.
[22] S. Wan, W. Mori, S. Yamada, S.I. Murahashi, Bull. Chem. Soc. Jpn. 62 (1989) 435.
[23] J. Korvenranta, H. Saarinen, M. Näsäkkälä, Inorg. Chem. 21 (1982) 4296.
[24] J.G. Mohanty, R.P. Singh, A. Chakravorty, Inorg. Chem. 14 (1975) 2178.
[25] J.G. Mohanty, A. Chakravorty, Inorg. Chem. 15 (1976) 2912.
[26] A.G. Lappin, M.C.M. Laranjeira, R.D. Peacock, Inorg. Chem. 22 (1983) 786.
[27] Y. Gok, K. Kantekin, Polyhedron 16 (1997) 2413.
[28] M.M. Aly, N.I.A. Shatti, Transition Met. Chem. 23 (1998) 361.
[29] M.N. Hughes, The Inorganic Chemistry of Biological Processes, Wiley, New York, 1981. p. 58.
[30] W.A. Wolkert, T.J. Hoffman, Chem. Rev. 99 (1999) 2269.
[31] Z.P. Deng, S. Gao, L.H. Huo, H. Zhao, Acta Crystallogr., Sect. E 61 (2005) m2214.
[32] V. Sharma, V. Sharma, R. Bohra, Transition Met. Chem. 32 (2007) 442.
[33] V. Sharma, V. Sharma, R. Bohra, J.E. Drake, M.B. Hursthouse, M.E. Light, Inorg. Chim. Acta 360 (2007) 2009.
[34] L.H.A. Terra, M.C. Areias, I. Gaubeur, M.E.V. Suez-Iha, Spectrosc. Lett. 32 (1999) 257.
[35] M.R. Maurya, S. Agarwal, M. Abid, A. Azam, C. Bader, M. Ebel, D. Rehder, J. Chem. Soc., Dalton Trans. (2006) 937.
[36] A.C. Cunha, J.M. Figueiredo, J.L.M. Tributino, A.L.P. Miranda, H.C. Castro, R.B. Zingali, C.A.M. Fraga, M.C.B.V. Souza, V.F. Ferreira, E.J. Barreiro, Bioorg. Med. Chem. 11 (2003) 2051.
[37] M.F. Iskander, L. El-Sayed, N.M.H. Salem, W. Haase, H.J. Lindner, S. Foro, Polyhedron 23 (2004) 23.
[38] E.W. Ainscough, A.M. Brodie, W.A. Denny, G.J. Finlay, S.A. Gothe, J.D. Ranford, J. Inorg. Biochem. 77 (1999) 125.
[39] T.B. Chaston, D.R. Richardson, J. Biol. Inorg. Chem. 8 (2003) 427.
[40] P.V. Bernhardt, P. Chin, D. Richardson, J. Biol. Inorg. Chem. 6 (2001) 801.
[41] M.M. Mostafa, K.M. Ibrahim, M.N.H. Moussa, Transition Met. Chem. 9 (1984) 243.
[42] N.M.H. Salem, L. El-Sayed, W. Haase, M.F. Iskander, J. Coord. Chem. 58 (2005) 1327.
[43] R. Dinda, P. Sengupta, S. Ghosh, T.C.W. Mak, Inorg. Chem. 41 (2002) 1684.
[44] R. Dinda, P. Sengupta, M. Sutradhar, T.C.W. Mak, S. Ghosh, Inorg. Chem. 47 (2008) 5634.
[45] R.A. Rowe, M.M. Jones, Inorg. Synth. 5 (1957) 113.
[46] S. Naskar, D. Mishra, R.J. Butcher, S.K. Chattopadhyay, Polyhedron 26 (2007) 3703.
[47] G.M. Sheldrick, SHELX, Programs for Crystal Structure Analysis, University of Göttingen, Germany, 1997.
[48] Clinical and Laboratory Standards Institute Methods for Dilution Antimicrobial Susceptibility Tests for Bacteria That Grow Aerobically, seventh ed., Approved Standard M7-A7, CLSI, Wayne, PA, USA, 2006.
[49] K. Nakamoto, in: Infrared and Raman Spectra of Inorganic and Coordination Compounds, Wiley, New York, 1986, pp. 241–242.
[50] S. Das, G.P. Muthukumaragopal, S.N. Pal, S. Pal, New J. Chem. 27 (2003) 1102.
[51] D. Li, S. Wang, H. Xu, Y. Yang, S. Zeng, J. Zhao, D. Wang, J. Dou, Inorg. Chim. Acta 365 (2011) 85.
[52] M. Moon, M. Pyo, Y.C. Myoung, C.I.I. Ahn, M.S. Lah, Inorg. Chem. 40 (2001) 554.
[53] S. Halder, R. Acharyya, S.M. Peng, G.H. Lee, M.G.B. Drew, S. Bhattacharya, Inorg. Chem. 45 (2006) 9654.
[54] A. Sarkar, S. Pal, Inorg. Chim. Acta 361 (2008) 2296.
[55] H. Glas, E. HerdTweck, G.R.J. Artus, W.R. Thil, Inorg. Chem. 37 (1998) 3644.
[56] Y. Sun, M. Melchior, D.A. Summers, R.C. Thompson, S.J. Retting, C. Orvig, Inorg. Chem. 37 (1998) 3119.
[57] M.R. Maurya, S. Khurana, C. Schulzke, D. Rehder, Eur. J. Inorg. Chem. (2001) 779.
[58] N. Sharma, M. Kumari, V. Kumar, J. Coord. Chem. 63 (2010) 1940.
[59] A.M. Ramadan, J. Inorg. Biochem. 65 (1997) 183.
[60] P.G. Avaji, C.H.V. Kumar, S.A. Patil, K.N. Shivananda, C. Nagaraju, Eur. J. Med. Chem. 44 (2009) 3552.
[61] Z.H. Chohan, S.H. Sumrra, M.H. Youssoufi, Eur. J. Med. Chem. 45 (2010) 2739.
[62] K. Tahira, S. Ali, S. Shahzadi, J. Coord. Chem. 64 (2011) 1871.
[63] K.S. Prasad, L.S. Kumar, S.C. Shekar, M. Prasad, H.D. Revanasiddappa, Chem. Sci. J. 2011 (2011). CSJ-12.
[64] H. Katherine, J.H. Thompson, J.H. McNeill, C. Orvig, Chem. Rev. 99 (1999) 2561.