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Original article

Oxovanadates: a novel probe for studying lipid–water interfaces

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Abstract

How water, metabolites and proteins associate and traverse the lipid interface is generally investigated by using probes with spectroscopic handles. Cellular confinement limits the tools of investigation to indirect approaches. Studies of a variety of different probes become important to understand the effects of confinement on chemical reactions and biological function. Confinement of water affects the properties of water and this effect is important for cellular systems. A versatile model system for studying the effect of water confinement on biological processes uses reverse micelles (RMs). Molecular probes are also used to investigate environments that are not readily accessible to direct measurements. Most of the dyes in use contain large hydrophobic chromophores and do not have size and structural flexibility to probe a surface that is both hydrophobic and hydrophilic as common in biological systems. We present the use of vanadium-containing probes for exploration of the fundamental properties of restricted water and lipid interfaces in RMs. The presence of a vanadium atom in these probes provides multiple handles such as chemical shifts, signal linewidth and lifetime experiments in the quadrupolar ^{51}V nuclei as well in ^{1}H and ^{13}C nuclei for investigations. The quadrupolar nuclei have a greater battery of useful spectroscopic parameters and combined with the conventional methods provide multiple handles in one probe. Furthermore, the vanadium-containing probe structure, charge and polarity can be modified for use in various biological settings. Here we introduce the concept and describe a few applications of this approach.

Keywords: Lipid interface; Polyoxometalates; Oxovanadates

1. Introduction

Understanding how lipid interfaces interact with simple solutes is important in biology. Water is a major component of the cytoplasm and the medium in which cellular transport of proteins and metabolites occurs. The mechanism of substrate transport from one locale to another is important to many biological processes. Biological fluids such as blood consist of more water than any other component. Water is the major components of most biological tissue. Fundamental information concerning transport of metabolites and other entities in water are important to understanding the distribution of nutrients and drugs in tissues and learning how they enter cells and distribute themselves throughout the body. A schematic diagram shown in Fig. 1 demonstrates how a solute can be located in the water pool (A), at the lipid interface (B) or deeply buried in the nonpolar part of the structure (C). However, difficulties in biological studies include the inherent complexity of the biological systems and the limitations of the available spectroscopic probes [1–4]. Development of new versatile probes and a deeper understanding of relevant chemical processes are critical for development of useful probes for biological systems.

The transition metal vanadium has an NMR active nucleus in a 99.75% natural abundance making it favorable for observation [5]. The ^{51}V nucleus has a quadruple moment of -5.2×10^{-30} m^2 which is in a range when signal widths are highly sensitive to the electric field gradients at the nucleus. The nuclear spin of 7/2 assures fast relaxation times and the broad lines are not generally a problem in part because of the large spectral window available [5]. ^{51}V NMR spectroscopy has been successfully used for characterization of novel vanadium complexes and contributed to the large increase in num-

Abbreviations: AOT, sodium bis(2-ethylhexyl)sulfosuccinate; CTAB, cetyltrimethylammonium bromide; NMR, nuclear magnetic resonance; RM, reverse micelle; $[VO_2dipic]^-$, dipicolinatodioxovanadium(V) anion; V_A V_B V_C, specific vanadium atoms shown in Fig. 1 illustration; V_{10}, decavanadate; V_1, vanadate monomer; V_2, vanadate dimer; V_4, vanadate tetramer; V_5, vanadate pentamer.

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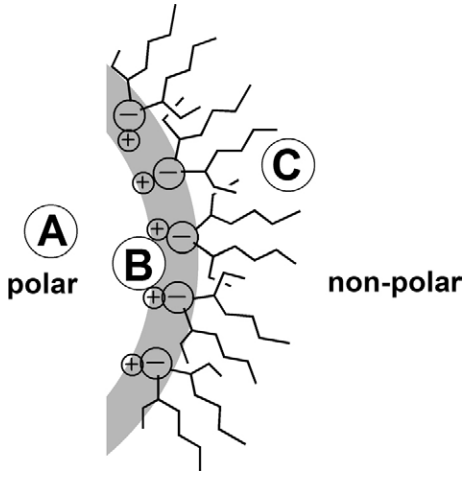

Fig. 1. An idealized illustration of a lipid interface with a negatively charged polar head group and two long aliphatic chains organized at the interface of a polar water pool.

ber of known vanadium(V) complexes [6]. Application of vanadium compounds as spectroscopic probes is convenient and effective utilizing ^{51}V NMR spectroscopy and the wide variety of compounds available, varying the number of vanadium atoms, the presence and absence of ligands and the compound size.

Vanadium chemistry is very versatile and many vanadium (V) complexes are often accessible [6]. The simple oxovanadates are generally prepared in the absence of ligands by adjusting the pH to a particular range. For example, the orange decavanadate is readily formed from pH 3–5. The colorless and simple oxovanadates form above neutral pH. The major challenge in the synthesis of simple vanadium(V) coordination compounds is to maintain the pH of the reaction solution in a pH range where the complex is stable and the components soluble. Since many coordination complexes form at pH 5, experimental conditions must be employed precluding formation of decavanadates. However, in this work we demonstrate that decavanadate formation can be very useful as a probe defining aqueous environments in confined media.

Two classes of vanadium compounds have so far been employed for characterization of the probe interaction with lipid interfaces [7,8]. The simple dipicolinatooxovanadate(V) complex, Fig. 2a, has been found to interact with organized self-assembled surfaces much more than with dispersed ions. In positively charged CTAB-RMs, the complex was found to place itself in the water pool with the polar headgroup oriented toward the polar charged surfactant head groups, and the hydrophobic tail oriented toward the water pool (location B in Fig. 1) [7]. In negatively charged AOT-reverse micelles (RMs) the probe penetrates the lipid interface and resides in the interface (near location C in Fig. 1) [8]. These probes are very different than the highly charged inorganic oxometalate-type vanadium-containing compounds [6,9].

Many oxovanadates have been characterized in detail including the yellow–orange decavanadate (V_{10}), Fig. 2b, and the colorless labile oligovanadates. The structure and stabilities of each oxovanadates vary, Table 1, and their distribution change depending on concentration, pH, ionic strength, tem-

Table 1
Oxovanadate stoichiometry, formation constants, chemical shifts and pK_a values[a]

Species	p, q	log β_{pq}[b]	pK_a	δ (^{51}V) (ppm)[c]
VO_4^{3-}	–2, 1	–21.31		–541.2
HVO_4^{2-}	–1, 1	–7.91	13.4	–538.8
$H_2VO_4^-$	0, 1		7.91	–560.4
VO_2^+	2, 1	6.97		–545.0
$V_2O_7^{4-}$	–2, 2	–15.13		–561.0
$HV_2O_7^{3-}$	1, 2	–5.39	9.74	–563.5
$H_2V_2O_7^{2-}$	0, 2	2.90	8.29	–572.7
$V_4O_{13}^{6-}$	–2, 4	–8.50		–566 to –585[d]
$HV_4O_{13}^{5-}$	–1, 4	0.4	8.9	–566 to –585[d]
$V_4O_{12}^{4-}$	0, 4	10.04		–577.6
$V_5O_{15}^{5-}$	0, 5	12.43		–586.0
$V_{10}O_{28}^{6-}$	4, 10	51.98		–422, –496, –513
$HV_{10}O_{28}^{5-}$	5, 10	58.12	6.14	–424, –500, –516
$H_2V_{10}O_{28}^{4-}$	6, 10	61.80	3.68	–425, –506, –524
$H_3V_{10}O_{28}^{3-}$	7, 10	63.37	1.57	–427, –515, –534

[a] Ionic strength = 0.6 M Na(Cl). Data taken from Ref. [16].
[b] log b for the equilibria $pH^+ + 1(H_2VO_4^-) = (H^+)_p(H_2H_2VO_4^-)_q$.
[c] δ ^{51}V relative to $VOCl_3$.
[d] A value in the indicated range has been reported.

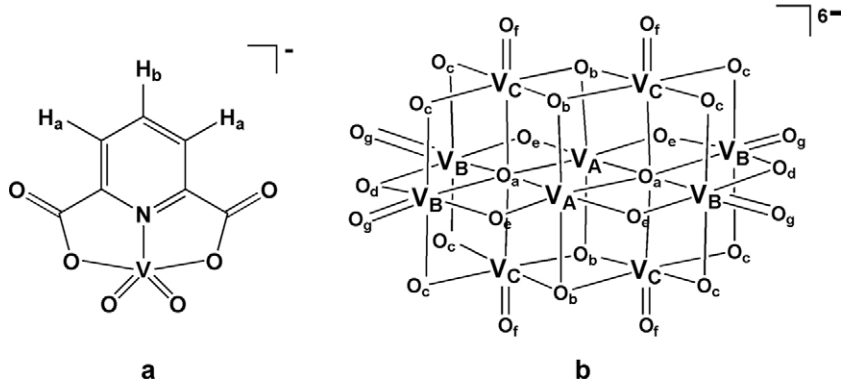

Fig. 2. The structure of the two vanadium-containing probes introduced in this work the dipicolinatooxovanadium(V) complex ($[VO_2dipic]^-$, a) and decavanadate ($V_{10}O_{28}^{6-}$, b).