



Inhibition of Na^+/K^+ - and Ca^{2+} -ATPase activities by phosphotetradecavanadate

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ABSTRACT

Polyoxometalates (POMs) are promising inorganic inhibitors for P-type ATPases. The experimental models used to study the effects of POMs on these ATPases are usually *in vitro* models using vesicles from several membrane sources. Very recently, some polyoxotungstates, such as the Dawson anion $[\text{P}_2\text{W}_{18}\text{O}_{62}]^{6-}$, were shown to be potent P-type ATPase inhibitors; being active *in vitro* as well as *in ex-vivo*. In the present study we broaden the spectrum of highly active inhibitors of Na^+/K^+ -ATPase from basal membrane of epithelial skin to the bi-capped Keggin-type anion phosphotetradecavanadate $\text{Cs}_{5.6}\text{H}_{3.4}\text{PV}_{14}\text{O}_{42}$ (PV_{14}) and we confront the data with activity of other commonly encountered polyoxovanadates, decavanadate (V_{10}) and monovanadate (V_1). The X-ray crystal structure of PV_{14} was solved and contains two *trans*-bicapped α -Keggin anions $\text{H}_x\text{PV}_{14}\text{O}_{42}^{(9-x)-}$. The anion is built up from the classical Keggin structure $[(\text{PO}_4)_4@(\text{V}_{12}\text{O}_{36})]$ capped by two $[\text{VO}]$ units. PV_{14} (10 μM) exhibited higher *ex-vivo* inhibitory effect on Na^+/K^+ -ATPase (78%) than was observed at the same concentrations of V_{10} (66%) or V_1 (33%). Moreover, PV_{14} is also a potent *in vitro* inhibitor of the Ca^{2+} -ATPase activity (IC_{50} 5 μM) exhibiting stronger inhibition than the previously reported activities for V_{10} (15 μM) and V_1 (80 μM). Putting it all together, when compared both P-type ATPases it is suggested that PV_{14} exhibited a high potential to act as an *in vivo* inhibitor of the Na^+/K^+ -ATPase associated with chloride secretion.

1. Introduction

Polyoxometalates (POMs) are inorganic anionic metal oxide clusters exhibiting a broad diversity of structures and outstanding properties leading to their application in many fields [1–5]. The usage of biologically active POMs for medical purposes is continuously increasing and thus attracting more and more attention from scientist coming from medical- and biology-related research areas [5–8]. P-type ATPases constitute a large family of ion pumps, which are found in all kingdoms of life and are responsible for many biologically essential processes assigning them important roles in health and diseases [9–12]. Therefore, P-type ATPases represent important pharmacological targets being

reflected by the substantial number of drugs targeting these ion pumps [11].

Forty years have passed since the discovery that the muscle inhibitor factor (MIF) and the Na^+/K^+ -ATPase inhibitor (present in commercial ATP) contained vanadium in the +V oxidation state (as vanadate VO_4^{3-}) [13]. Actually, it is well known that vanadate ions or vanadium complexes inhibit or stimulate the activity of many enzymes [14]. In fact, the serendipitous discovery of vanadate as a Na^+/K^+ -ATPase inhibitor [13] leads us, 40 years after, to the discussion on POMs as putative drugs in the treatment of several diseases in which the molecular targets are established to be precisely the ion pumps such as Na^+/K^+ -ATPase and Ca^{2+} -ATPase [12,14–16]. Furthermore, POMs are

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particularly known as inhibitors of others enzymes such as phosphatases, ecto-ATPases or cholinesterases [6–8,14,17–21]. For the majority of common drugs used in therapy as P-type ATPase inhibitors, the main target is the Na^+/K^+ -ATPase [11]. These drugs are being investigated for several disease treatments such as heart failure, antipsychotic, anti-malaria and also used as anesthetics, tumor promoter, antibiotic and insulin mimetic agents, and, very importantly, they present inhibitory capacity not so different from POMs [11,12]. Previously published data regarding the Ca^{2+} -ATPase inhibition are available for decanibate (abbreviated as Nb_{10}) [$\text{Nb}_{10}\text{O}_{28}$] $^{6-}$ ($\text{IC}_{50} = 35 \mu\text{M}$) [16] and for Keggin-based polyoxotungstates (POTs) such as mono-substituted Keggin structure [$\text{TiW}_{11}\text{CoO}_{40}$] $^{8-}$ (4 μM), tri-lacunary [$\text{A}-\alpha\text{-SiW}_9\text{O}_{34}$] $^{10-}$ (16 μM) and [$\text{B}-\alpha\text{-AsW}_9\text{O}_{33}$] $^{9-}$ (20 μM), lacunary Dawson type [$\alpha\text{-H}_2\text{P}_2\text{W}_{12}\text{O}_{48}$] $^{12-}$ (11 μM), and also for [$\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})$] $^{14-}$ (28 μM) [22].

Herein, we report and compare for the first time the effects of three polyoxovanadates (POVs), namely phosphotetradecavanadate, $\text{H}_x\text{PV}_{14}\text{O}_{42}^{(9-x)-}$ (abbreviated as PV_{14}), monovanadate $\text{H}_x\text{VO}_4^{(3-x)-}$ (V_1) and decavanadate $\text{H}_x\text{V}_{10}\text{O}_{28}^{(6-x)-}$ (V_{10}) on the activity of P-type ATPases using two different experimental models: the *in vitro* Ca^{2+} -ATPase activity of sarcoplasmic reticulum (SR) vesicles and the *ex-vivo* activity of Na^+/K^+ -ATPase using a model obtained from basal membrane of epithelial skin. To our knowledge those represent the first *ex-vivo* studies describing the effects of PV_{14} and V_{10} in the processes of epithelial chloride secretion energized by basolateral Na^+/K^+ -ATPase activity. Furthermore, we also provide full characterization of the PV_{14} prepared as $\text{Cs}_{5.6}\text{H}_{3.4}\text{PV}_{14}\text{O}_{42}$ including X-ray crystal structure analysis.

2. Experimental section

2.1. Materials and characterization methods

Vanadium and cesium contents were determined by ICP-MS using Perkin-Elmer ELAN 6000 instrument. FT-IR spectra were collected on a Bruker Vertex 70 instrument by ATR method. ^{51}V nuclear magnetic resonance spectroscopy measurement of 1 mM PV_{14} aqueous solution (with 10% of D_2O , 20 °C) was taken on a Bruker AV II+ 500 MHz instrument operating at 131.60 MHz for ^{51}V nucleus (2500 scans, accumulation time 0.05 s, relaxation delay 0.01 s). Chemical shift values are given with reference to VOCl_3 (0 ppm) as a standard.

The X-ray intensity data were measured on a Bruker X8 Apex2 diffractometer equipped with multilayer monochromators, Mo K/ α ($\lambda = 0.71073 \text{ \AA}$) INCOATEC micro focus sealed tubes and Oxford cooling system. The structure was solved by Patterson methods and refined by full-matrix least-squares techniques. Non-hydrogen atoms were refined with anisotropic displacement parameters. The following software was used: Bruker SAINT software package [23] using a narrow-frame algorithm for frame integration, SADABS [24] for absorption correction, OLEX2 [25] for structure solution, refinement, molecular diagrams and graphical user-interface, Shelxl [26] for refinement and graphical user-interface, SHELXS-2016 [27] for structure solution, SHELXL-2016 [28] for refinement, Platon [29] for symmetry search and check. The graphic for Fig. 1 was obtained with Diamond 4.5.3 [30].

Common analytical solutions, reagents and materials used for the preparation of the calcium pump vesicles and for the kinetic studies described below were prepared from reagents obtained from Sigma-Aldrich (Portugal, Austria). The stock solutions of monovanadate (V_1 , 50 mM, pH 10.5) and decavanadate (V_{10} , 5 mM, pH 4.0) were prepared similarly as in our previous studies on V_{10} interactions with proteins and *in vivo* studies [14,16,17]. Briefly, NH_4VO_3 was dissolved in milliQ water with heating, the pH was adjusted to 10.5 with NaOH and the solution was heated until colorless solution was obtained. After cooling, the solution was splitted into two parts. The pH of one of them was adjusted to 4.0 with HCl to obtain an orange solution of V_{10} . The other solution is named monomeric vanadate solution V_1 .

2.2. Preparation and characterization of phosphotetradecavanadate

The bicapped Keggin-type phosphotetradecavanadate $\text{Cs}_{5.6}\text{H}_{3.4}\text{PV}_{14}\text{O}_{42} \cdot 12\text{H}_2\text{O}$ (PV_{14}) was synthesized by modification of published procedures [31–33]: NaVO_3 (4.5 g, 37 mmol) was dissolved in 40 mL of hot distilled water. H_3PO_4 (0.636 mL, 9.3 mmol) was added and the pH was adjusted to 2.5 with conc. HNO_3 . The solution was heated to 50 °C, CsCl (2 g, 12 mmol) was gradually added into it and the solution was maintained at 50 °C several hours to provide red cubic crystals of the title compound. Elemental analysis for $\text{Cs}_{5.6}\text{PV}_{14}\text{H}_{27.4}\text{O}_{54}$ (calc.): V 31.2 (31.3), Cs 29.7 (30.0). Stock solutions (1 mM aqueous solution, pH 5.5) of PV_{14} for inhibition studies were prepared daily wherever adequate by dissolution of the solid compound in water and kept on ice during the utilization.

2.3. Ca^{2+} -ATPase (*in vitro*) and Na^+/K^+ -ATPase (*ex-vivo*) inhibition studies

Detailed description of experimental procedures necessary for inhibition studies (preparation of sarcoplasmic reticulum Ca^{2+} -ATPase vesicles and epithelial short circuit current in Ussing chambers *ex-vivo*) can be found in [16,22]. In short: Isolated sarcoplasmic reticulum (SR) vesicles prepared from rabbit skeletal muscles as described elsewhere [16] were suspended in 0.1 M KCl, 10 mM HEPES (pH 7.0), diluted 1:1 with 2.0 M sucrose and frozen in liquid nitrogen prior to storage at -80°C . The ATPase activity and the inhibition of POVs solutions was measured taken into consideration the decrease of the OD (Optical density) per minute in the absence (100% activity) and in the presence of several PV_{14} concentrations, according to described elsewhere [16]. All experiments were performed at least in triplicate. The inhibitory power of the investigated PV_{14} was evaluated determining IC_{50} values meaning the POM concentration inducing 50% of Ca^{2+} -ATPase inhibition of the enzyme activity. Aqueous stock solutions of these PV_{14} were prepared in concentrations up to 1 or 0.5 mM stock solution in water considering a M_r of 2380.01 g/mol. Solutions of PV_{14} were prepared daily wherever adequate by dissolution of the solid compounds in water and kept on ice during the utilization to avoid putative POM decomposition.

For the *ex-vivo* study killifish (*F. heteroclitus*, 4–8 g) was collected with fish traps from the saltmarshes of Ria Formosa (Faro) and maintained in Ramalheite Marine Station (CCMar, University of Algarve, Faro, Portugal). All animal protocols were performed under a “Group C” license from the Direcção-Geral de Veterinária, Ministério da Agricultura, do Desenvolvimento Rural e das Pescas, Portugal.

The experimental setup for the *ex-vivo* study is illustrated in Fig. 1A. ET_{50} is the effective time (in minutes) necessary to reach 50% of the maximum effects for each POM concentration. The maximum inhibitory effect (%) of the ATPase activity by the POVs solutions and the effective time (ET_{50}) necessary to reach 50% of the maximum effects (in minutes) were measured, taken into consideration the % decrease of short circuit current (Isc , $\mu\text{A}/\text{cm}^2$) in the absence (100% activity) and upon addition of PV_{14} (Fig. 1B). In the opercular epithelium of killifish used for our studies, Isc is a direct measure of apical chloride secretion mediated by chloride channels, which relies on an intact basolateral Na^+/K^+ -ATPase to function [34,35]. Methodology for *ex-vivo* opercular epithelia preparation followed our current methods [22,36]. Fish were anaesthetized with 2-phenoxyethanol (1:2000 v/v), sacrificed by decapitation and the cranium was cut longitudinally. The gills and other tissue remains were removed carefully and the epithelial skin covering the opercular bone were dissected out and transferred to fresh-gassed saline (99.7:0.3 O_2/CO_2) with the following composition (all values in mM): NaCl, 160; MgSO_4 , 0.93; NaH_2PO_4 , 3; CaCl_2 1.5, NaHCO_3 17.85, KCl 3; Glucose 5.5 HEPES 5; pH 7.8. Measurement of short circuit current (Isc , $\mu\text{A}/\text{cm}^2$) was performed in symmetric conditions under voltage clamp to 0 mV. Open circuit potential (Vt , mV) and Isc were monitored by means of Ag/AgCl electrodes connected to

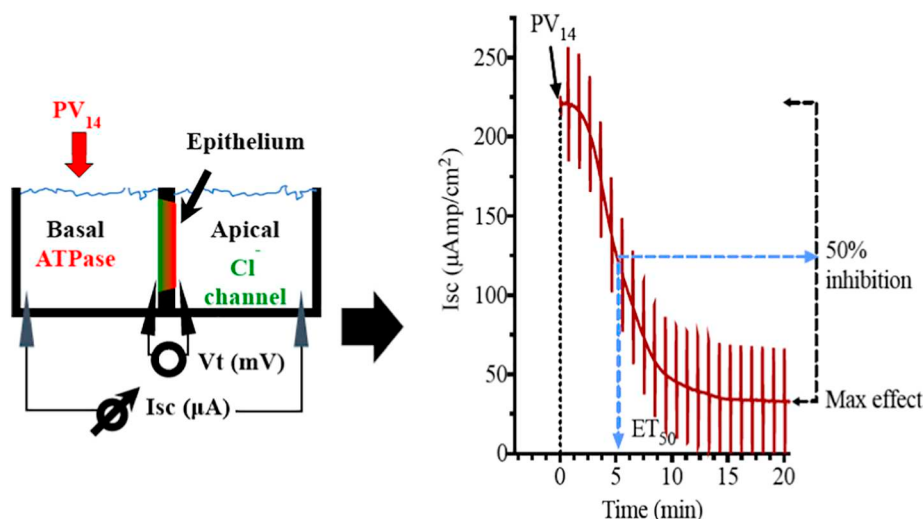


Fig. 1. A) Schematic representation of the experimental setup of the opercular epithelium of killifish used for our *ex vivo* studies. Isc was measured in voltage clamp, and in this model represents chloride secretion. The process is energized by basolateral Na^+/K^+ -ATPase and chloride is secreted apically via a chloride channel. B) Original trace of the effect of short circuit current (Isc, $\mu\text{A}/\text{cm}^2$) in the opercular epithelium of killifish mounted in Ussing chambers and kept under voltage clamp ($V_t = 0$ mV) after PV_{14} addition. Effective time 50 (ET_{50}), time necessary to reach 50% of the maximum effects is shown in minutes; and maximum inhibitory effects are calculated as the % of basal values.

the chambers by 3 mm bore agar bridges (1 M KCl in 3% agar). Clamping of epithelia to 0 mV and recording of Isc was performed by means of VCC600 voltage clamp amplifiers (Physiologic Instruments, San Diego, USA). Bioelectrical data was continuously digitized through a Lab-Trax-4 (WPI, Sarasota, US) onto a Macbook laptop using Labscribe3 Software (Iworks systems, Dover, US). All experiments were performed at least in triplicate. Calculations of ET_{50} and Maximum effect were performed using GraphPad Prism version 6.00 for Macintosh (GraphPad Software, La Jolla California USA).

3. Results and discussion

3.1. Characterization of phosphotetradecavanadate

The non-stoichiometric composition found for $\text{Cs}_{5.6}\text{H}_{3.4}\text{PV}_{14}\text{O}_{42} \cdot 12\text{H}_2\text{O}$ (PV_{14}) is in good agreement with the previously reported analogical salts $\text{K}_{5.72}\text{H}_{3.28}[\text{PV}_{14}\text{O}_{42}]$ [31] and $\text{Rb}_{5.89}\text{H}_{3.11}[\text{PV}_{14}\text{O}_{42}]$ [37]. The characteristic bands in IR spectra represent P=O (1053 cm^{-1}) and V=O stretching vibrations ($934 \text{ vs } + 862 \text{ cm}^{-1}$), as well as vibrations of various V–O–V bridges (two groups of bands at $800, 741, 709 \text{ cm}^{-1} + 590, 557, 476, 428 \text{ cm}^{-1}$) (Fig. S2).

^{51}V NMR spectrum of a 1 mM solution of PV_{14} (Fig. 2) revealed three characteristic peaks at -592 ppm , -574 ppm , -524 ppm in the ratio 4:8:2. The chemical shift at -524 ppm corresponds to vanadium atoms of the two capping V=O units that are pentacoordinated, the remaining peaks corresponds to octacoordinated vanadium atoms of the Keggin cage connected to the capping V atoms through oxido bridges (-574 ppm) or not connected (-592 ppm). Based on published speciation studies in the ternary $\text{H}^+/\text{H}_2\text{VO}_4^-/\text{H}_2\text{PO}_4^-$ system with found chemical shifts -589 ppm , -572 ppm , -521 ppm for

$\text{H}_3[\text{PV}_{14}\text{O}_{42}]^{6-}$ species and -598 ppm , -580 ppm , -530 ppm for $\text{H}_4[\text{PV}_{14}\text{O}_{42}]^{5-}$ species [38], the NMR shows that the found chemical shifts lie in the expected region.

The X-ray crystal structure of PV_{14} (Fig. S1; Table S2 and Table S3) was solved in $P-4n2$ space group and the unit cell contains two *trans*-bicapped α -Keggin anions $\text{H}_x\text{PV}_{14}\text{O}_{42}^{(9-x)-}$ (Fig. 3). The anion is built up from the classical Keggin structure $[(\text{PO}_4)_4@(\text{V}_{12}\text{O}_{36})]$ capped by two [VO] units. The V=O groups are located in surface moieties formed by four adjacent oxygen atoms at V–O distances in the range $1.838\text{--}2.238 \text{ \AA}$ (Fig. S1). The two [VO] units are in opposition and occupy three different pairs of positions on the surface of the Keggin anion with various occupancies giving the overall sum formula as determined by ICP-MS analysis. The high degree of disorder in the area of counter ions and water molecules forced the use of squeeze. According to the result of elemental analysis (5.6 Cs), the excluded volume ($1208.2 \text{ \AA}^3$) and number of electrons (1112.0), the following maximum content is possible: 12 Cs and up to $\sim 45 \text{ H}_2\text{O}$ molecules. This leads to ~ 1112 electrons and $\sim 1200 \text{ \AA}^3$ by the model. This is in very good accordance to approximately twelve charges of the two POMs in the unit cell needed. The analogous compounds $\text{K}_{5.72}\text{H}_{3.28}[\text{PV}_{14}\text{O}_{42}]$ [32] and $\text{Rb}_{5.89}\text{H}_{3.11}[\text{PV}_{14}\text{O}_{42}]$ [37] also exhibited the same disorder that was treated similarly.

3.2. Inhibition of Ca^{2+} -ATPase by phosphotetradecavanadate: *in vitro* studies

The effect of phosphotetradecavanadate (PV_{14}) on the activity of sarcoplasmic reticulum Ca^{2+} -ATPase from skeletal muscle (*in vitro*

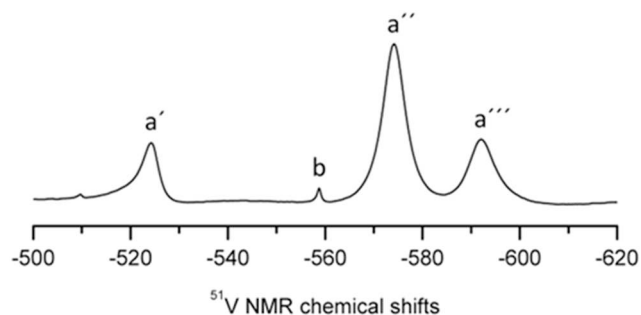


Fig. 2. ^{51}V NMR spectrum of 1 mM aqueous PV_{14} solution at autogenous pH (5.5). Legend: a' , a'' , a''' $\text{H}_x\text{PV}_{14}\text{O}_{42}^{(9-x)-}$; b H_3VPO_7^- .

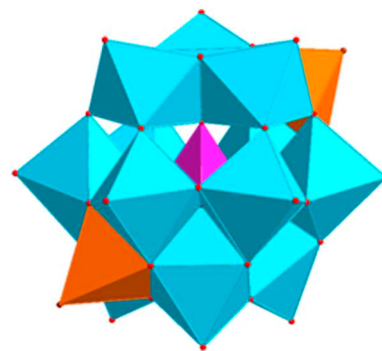


Fig. 3. Polyhedral representation of the structure of $\text{H}_x\text{PV}_{14}\text{O}_{42}^{(9-x)-}$ anion in PV_{14} as revealed by X-ray structure analysis. Polyhedron legend: pink $\{\text{PO}_4\}$, blue $\{\text{VO}_6\}$, orange $\{\text{VO}\}$ capping unit.

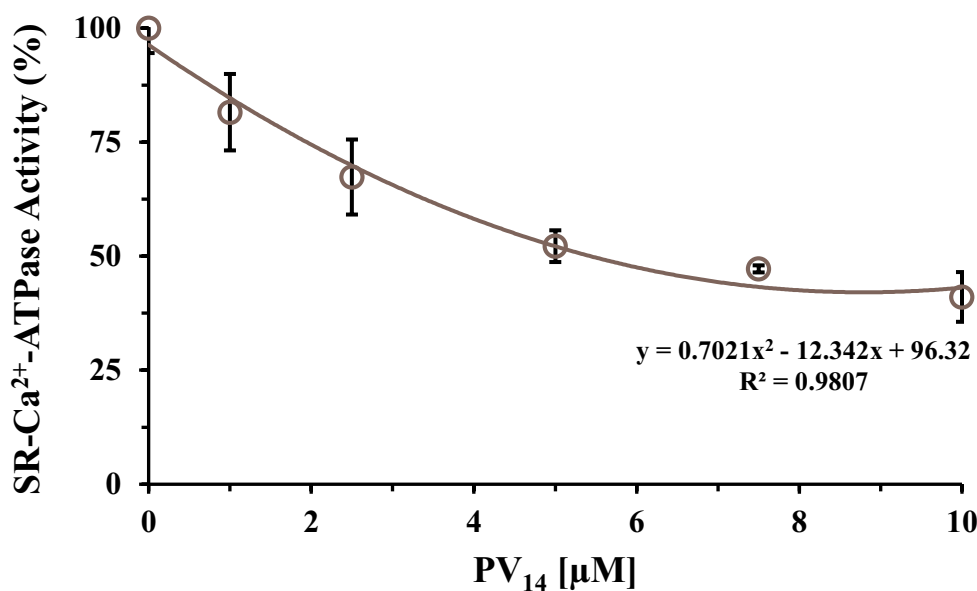


Fig. 4. Inhibition of Ca^{2+} -ATPase activity by PV_{14} . Ca^{2+} -ATPase was measured spectrophotometrically at 340 nm and 22 °C, using the coupled enzyme pyruvate kinase/lactate dehydrogenase assay. The experiments were initiated after the addition of 10 μg/mL calcium ATPase, in the presence or absence of 4% (w/w) of calcium ionophore A23187. Data are plotted as means $\pm$ SD. The results shown are the average of triplicate experiments.

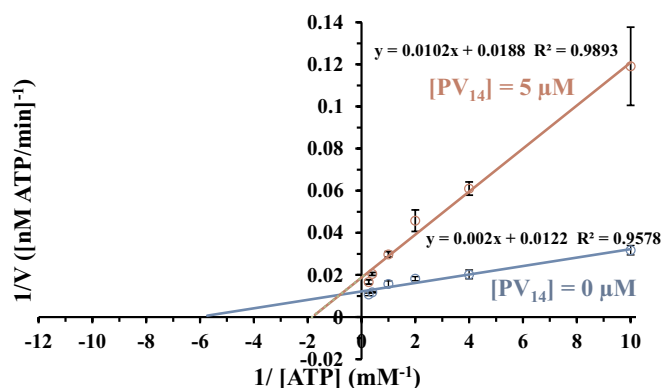


Fig. 5. Lineweaver-Burk plots of Ca^{2+} -ATPase activity in the absence (blue) and in the presence (orange) of 5 μM of the polyoxometalate PV_{14} . The plots were used for determining the type of enzyme inhibition. The POM PV_{14} presented a mixed type of inhibition. Data are plotted as means $\pm$ SD. The results shown are the average of triplicate experiments.

model) was investigated. It was observed that PV_{14} inhibits the Ca^{2+} -ATPase activity, expressed as a percentage of the control obtained without inhibitor, in a concentration dependent manner (Fig. 4). The inhibitory power of PV_{14} was evaluated using IC_{50} values (POM concentration at which it induces 50% of Ca^{2+} -ATPase inhibition of the enzyme activity) and the IC_{50} value of $5.4 \pm 0.5 \mu\text{M}$ was obtained. Ca^{2+} -ATPase IC_{50} values of inhibition below 1 μM were previously determined for polyoxotungstates (POTs) such as $[\alpha\text{-P}_2\text{W}_{18}\text{O}_{62}]^{6-}$ (0.6 μM) and $[\text{H}_{10}\text{Se}_2\text{W}_{29}\text{O}_{103}]^{14-}$ (0.3 μM), whereas the lowest potency was observed for $[\text{TeW}_6\text{O}_{24}]^{6-}$ ($\text{IC}_{50} = 200 \mu\text{M}$) [22]. It was previously determined that decavanadate V_{10} ($\text{IC}_{50} = 15 \mu\text{M}$) is more potent Ca^{2+} -ATPase inhibitors than V_1 ($\text{IC}_{50} = 80 \mu\text{M}$). Herein, we show that PV_{14} is the strongest inhibitor of the calcium pump ($\text{IC}_{50} = 5 \mu\text{M}$) among so far investigated vanadates. For both Nb_{10} and V_{10} , it was previously observed that they showed to be Ca^{2+} -ATPase non-competitive inhibitors regarding the natural ligand Mg-ATP [16]. PV_{14} presented a mixed type inhibition (Fig. 5), as was previously observed for $[\alpha\text{-P}_2\text{W}_{18}\text{O}_{62}]^{6-}$ and $[\text{TeW}_6\text{O}_{24}]^{6-}$ [22] suggesting that it can interact with the Ca^{2+} -ATPase whether or not the enzyme has already bound substrate and pointing out to the existence of two distinct protein binding sites for these types of POMs. Only for V_{10} a binding site in the Ca^{2+} -ATPase was previously described, involving at least three

protein domains including the phosphorylation and the nucleotide binding sites [39]. Studies about the type of inhibition and the mechanism of action of the other POMs interactions with P-type ATPases are to our knowledge still to be determined [16,17,22].

3.3. Inhibition of Na^+/K^+ -ATPase by phosphotetradecavanadate: ex-vivo studies

As pointed out in Fig. 1, modification of Isc provides an immediate read-out of inhibitory/stimulatory effects on either the apical chloride channel, or the basolateral Na^+/K^+ -ATPase induced by PV_{14} . Isc is measured in voltage clamp, and in this model represents chloride secretion. The process is energized by basolateral Na^+/K^+ -ATPase and chloride is secreted apically via a chloride channel. In this polarized epithelium, both mechanisms are required to be intact to sustain the process of secretion. Therefore, inhibitory effects of POMs on the basolateral side (where Na^+/K^+ -ATPase is located) result in inhibitory effects on Isc. Herein, it was observed that when PV_{14} was added to the basal side (Fig. 1), it does inhibit the Na^+/K^+ -ATPase activity (expressed as the % of maximum inhibition, in a concentration dependent manner, Fig. 6A). Thus, for 10 μM a maximum inhibition of 78% of the basal current was observed whereas a 50% inhibition is obtained for even less than 1 μM PV_{14} . On the other hand, the addition of PV_{14} to the apical side was not accompanied by an effect on Isc, ruling out chloride channels as putative targets of PV_{14} , at least in a range of concentrations up to 10 μM. From the data of Fig. 6A, we calculated an IC_{50} values of $1.4 \pm 0.1 \mu\text{M}$ for the ex-vivo Na^+/K^+ -ATPase inhibition. In addition, it has to be noted that besides the maximum inhibitory effect (providing information about inhibitor efficacy) also ET_{50} values (providing information about inhibition velocity) can be appreciated to characterize the biological effects of the inhibitor. It was observed that the value of ET_{50} decreases from 21 to 7 min upon increasing PV_{14} concentration (Fig. 6B). When comparing different POMs, this negative correlation does necessary mean that the lowest ET_{50} value implies a higher inhibition. In fact, it was observed that decavanadate at the same concentration (10 μM) exhibits the maximum inhibition of 66% and an ET_{50} of 14 min; whereas for the monomeric vanadate (at 10 μM) only 33% of maximum inhibition was observed, but a lower ET_{50} was determined (6 min).

A simultaneous comparison of these three vanadate species, PV_{14} , V_{10} and V_1 at the same concentration of 10 μM (Fig. 7) clearly illustrates that PV_{14} (blue line) is the most potent ex-vivo inhibitor (78%

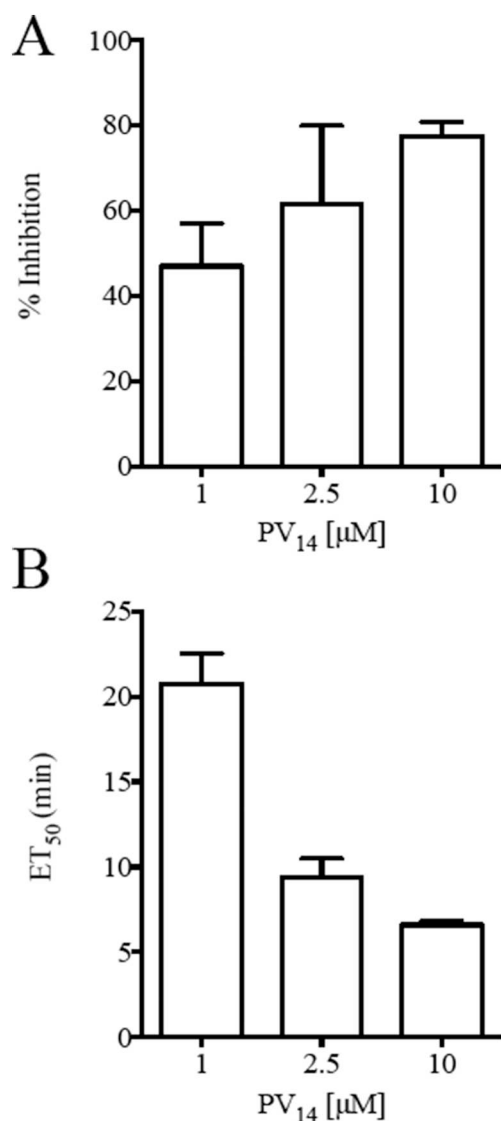


Fig. 6. A) Maximum inhibitory effects are calculated as the % of basal values and B) Effective time 50 (ET₅₀), time necessary to reach 50% of the maximum effects (shown in minutes); obtained for 1, 2.5 and 10 μM PV₁₄ concentrations. Data are plotted as means ± SD. The results shown are the average of triplicate experiments at 22 °C.

after 30 min upon addition), whereas for decavanadate (red) and vanadate (green) only minor effects were observed. It can be also observed, a constant height of the current deflections used to calculate tissue resistance implying that the *ex-vivo* preparation maintained its integrity and selectivity before and after POM exposure (Fig. 7). For these studies a positive control experiment was performed with the conventional Na⁺/K⁺-ATPase inhibitor ouabain. Ouabain (at 10 μM) showed a maximum inhibition value of 100% and an ET₅₀ of 3.2 min [22]. By inhibiting the basolateral Na⁺/K⁺-ATPase activity, ouabain concomitantly prevents apical chloride secretion. Cs⁺, in contrast with rubidium, is known not to affect the activity of this type of enzyme [40].

Let us briefly comment on the mechanism of P-type ATPases inhibition by POMs. POMs clearly exhibit different types of interaction with different P-type ATPases [12,14]. For example, the orthotungstate (HWO₄²⁻) presents a very low inhibition capacity (IC₅₀ = 1.5 mM) for the Na⁺/K⁺-ATPase [15], while for another ion pump, SR Ca²⁺-ATPase is the IC₅₀ = 400 μM [16]. Herein, taking into account the Ca²⁺-ATPase IC₅₀ values of inhibition for PV₁₄ (IC₅₀ = 5 μM) and V₁₀

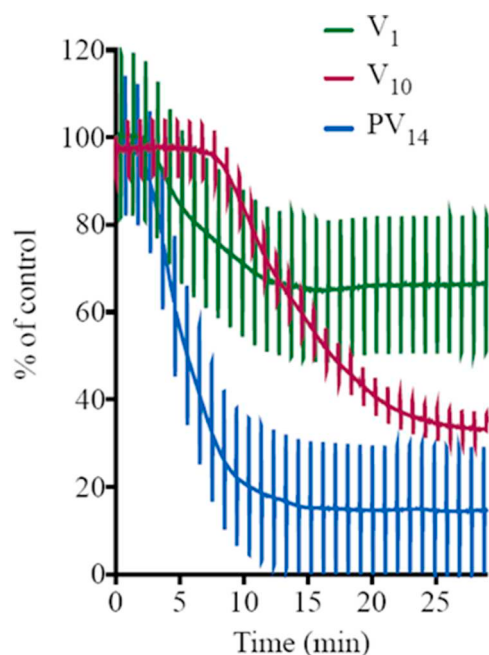


Fig. 7. PV₁₄, V₁₀ and V₁ inhibition (%) of the Na⁺/K⁺-ATPase activity from basal membrane of the skin epithelia. PV₁₄ (10 μM) inhibited 78% with an ET₅₀ of 6.4 min (blue) whereas lower effects were observed for V₁₀ (red) (66% inhibition, ET₅₀ 13.7) and for V₁ (green) (33% and ET₅₀ 6.4 min). Perpendicular lines were used to calculate tissue resistance. As it can be observed, the *ex vivo* epithelia preparations retained integrity and selectivity after compounds exposure.

(IC₅₀ = 15 μM) apparently the lower negative charge (−6) for V₁₀, at physiological pH and according to its pK_as values [14,16], in comparison to PV₁₄ (−9) is not favoring enzyme inhibition. Very recently, for high affinity POTs, exhibiting IC₅₀ values lower than 16 μM, it was described a correlation between their activity (IC₅₀ value) and their charge density, as well as by volume of POM anion [22]. Also recently, a combination of NMR studies, *ab initio* calculations and crystallographic analysis point out to specific molecular interactions between H₃PW₁₂O₄₀ or H₄SiW₁₂O₄₀ and the Na⁺/K⁺-ATPase [41]. POMs-protein interactions observed previously with myosin, actin and calcium ATPase [12,14,16,17,22,42,43] were described to be mostly of electrostatic nature including hydrogen bonds, but could also involve direct interaction with cysteins, as described for the P-type ATPase and actin [17,43]. Thus, besides electrostatic interactions, specific bonding modes underpinning their relative affinities and site recognition, and the structure and accessibility of the ATPase site for each crystallographically defined enzyme/pump relative to the inhibitory effectiveness of each POM are still to be determined [44–46]. In conclusion, the study of protein-POMs interactions is of utmost importance to explain and improve inhibition of certain enzymes for potential drug development [47–49].

As referred above, only few studies described POMs as inhibitors of the hydrolytic activity of several P-type ATPases [15,16]. In these P-type ATPases studies, normally vesicles from cellular membranes or organelles are used and constitute *in vitro* models for the study of POMs toxicity effects. However, in the majority of these studies, the stability, as well others factors, of the compounds and/or the putative decomposition into others species are not taken in consideration. Thus, this possibility must be considered and several papers were published over the last years [49–56]. Therefore, if the polyoxometalates species responsible for the observed effects are not always possible to be determined, participation of other species than the ones initially added to the biological system should be taken into account [49–57].

In fact, regarding the *in vitro* studies of POMs for the P-type ATPases

[15,16] it is possible to find, for instance, different experimental conditions such as temperature (25 and 37 °C), different times upon incubation depending on the kinetic studies used (2, 15 or 30 min) and of course different concentration range due to different IC_{50} values of ATPase activity inhibition. After incubation, both higher temperature and time would favor the decomposition of the added POM and therefore the appearance of different species that might also have a contribution for the observed inhibitory effects.

In this paper, the temperature was maintained for both *in vitro* and *ex-vivo* studies but the time after addition of the PV_{14} were clearly different, 1 min for the Ca^{2+} -ATPase assays, and 5 to 10 min incubation for the Na^{+}/K^{+} -ATPase assays. The determination of the inhibitory capacity needs also different times, 2–3 min for the Ca^{2+} -ATPase and 30 min for the Na^{+}/K^{+} -ATPase. Moreover, the mediums are different and also with slight different pH values. Therefore, the experimental conditions are not always favoring the putative comparison with different experimental conditions and methodologies.

In previous studies with V_{10} and Ca^{2+} -ATPase and other muscle proteins (such as myosin and actin) the putative reduction of vanadate was always taken in consideration [14,43,49]. In fact, reduction of V_{10} to oxidovanadium(IV) (VO^{2+}), was previously observed upon actin interaction, but only after 90 min incubation and with huge amounts of protein. Moreover, in the presence of the natural ligand (ATP) the vanadate reduction was not observed, suggesting that decavanadate interaction at the actin ATP binding is needed for the reduction of vanadate [43,49]. Herein, at the experimental *in vitro* and *in vivo* conditions the redox stability of PV_{14} during the biological measurements would be hard or impossible to be determined not only because of the concentrations used, in the order of μM , but also because of the time upon exposition, that is in the scale of a few minutes. Still, it is well known that intracellular V(V) can be reduced to oxidovanadium (IV) [58–61].

Putting it all together, and taking into account the IC_{50} values determined, the Keggin type polyoxovanadate PV_{14} exhibited a high potential to act as an *in vivo* inhibitor of the Na^{+}/K^{+} -ATPase than V_{10} or V_1 . However, as referred before for V_{10} [49], and also due to the vanadium complex chemistry and biochemistry we cannot exclude that besides PV_{14} the observed effects might be due to other vanadate or even to vanadyl species. Therefore, strong efforts are needed to confirm the biologically active POMs species.

4. Conclusions

The X-ray crystal structure of PV_{14} was solved and contains two *trans*-bicapped α -Keggin anions $H_xPV_{14}O_{42}^{(9-x)-}$. The anion is built up from the classical Keggin structure $[(PO_4)_4@ (V_{12}O_{36})]$ capped by two [VO] units. Phosphotetradecavanadate ($Cs_{5.6}H_{3.4}PV_{14}O_{42} \cdot 12H_2O$) synthesized and characterized in this work is the best so far investigated member of the alkali metals family of phosphotetradecavanadates, therefore it was reasonable to employ it in the inhibition studies of P-type ATPases. Ca^{2+} -ATPase activity from sarcoplasmic reticulum is inhibited by PV_{14} with the $IC_{50} = 5 \mu M$. This is about ten times higher than IC_{50} values reported for highly active POMs such as $[\alpha-P_2W_{18}O_{62}]^{6-}$ ($0.6 \mu M$), but on the other hand PV_{14} is 3 times more potent than V_{10} ($15 \mu M$) and much more potent than Nb_{10} ($35 \mu M$) and $[TeW_6O_{24}]^{6-}$ ($\approx 200 \mu M$). Similarly as described before for $[\alpha-P_2W_{18}O_{62}]^{6-}$ and $[TeW_6O_{24}]^{6-}$ a mixed type of inhibition was observed for PV_{14} . Therefore, a different mode of interaction with the Ca^{2+} -ATPase than the one observed for V_{10} and Nb_{10} (shown to be non-competitive inhibitors) must be involved. However, PV_{14} was shown to be the most potent Na^{+}/K^{+} -ATPase inhibitor when using an *ex-vivo* model obtained from basal membrane of the skin epithelia. Thus, for the *ex-vivo* Na^{+}/K^{+} -ATPase activity an IC_{50} value of $1.4 \mu M$ was observed. This *ex-vivo* model seems to be a very specific model to study the effects of POMs in the processes of epithelial chloride secretion energized by basolateral Na^{+}/K^{+} -ATPase activity.

Abbreviations

IC_{50}	concentration that induces 50% of Ca^{2+} -ATPase inhibition of the enzyme activity
ET_{50}	the effective time (in minutes) necessary to reach 50% of the maximum effects.
Nb_{10}	decaniobate, niobate oligomer containing 10 niobate units
POMs	Polyoxometalates
POTs	Polyoxotungstates
POVs	Polyoxovanadates
PV_{14}	phosphotetradecavanadate
SR	sarcoplasmic reticulum
V_1	vanadate, monomeric vanadate containing 1 vanadate units
V_{10}	decavanadate, vanadate oligomer containing 10 vanadate units

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Appendix A. Supplementary data

Supplementary data CCDC 1886317 contains the supplementary crystallographic data for PV_{14} . 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. These data include experimental details on inhibition studies, crystal data and structure refinement details. MOL files and InChIKeys of the most important compounds described in this article. Supplementary data to this article can be found online at doi:<https://doi.org/10.1016/j.jinorgbio.2019.110700>.

References

- [1] X. Chen, S. Yan, H. Wang, Z. Hu, X. Wang, M. Huo, Carbohydr. Polym. 117 (2015) 673–680.
- [2] S.S. Wang, G.Y. Yang, Chem. Rev. 115 (2015) 4893–4962.
- [3] L. Mohapatra, K.M. Parida, Phys. Chem. Chem. Phys. 16 (2014) 16985–16996.
- [4] M.A. Moussawi, N. Leclerc-Laronze, S. Floquet, P.A. Abramov, M.N. Sokolov, S. Cordier, A. Ponchel, E. Monflier, H. Bricout, D. Landy, M. Haouas, J. Marrot, E. Cadot, J. Am. Chem. Soc. 139 (2017) 12793–12803.
- [5] A. Bijelic, A. Rompel, Acc. Chem. Res. 50 (2017) 1441–1448.
- [6] T. Sun, W. Cui, M. Yan, G. Qin, W. Guo, H. Gu, S. Liu, Q. Wu, Adv. Mater. 28 (2016) 7397–7404.
- [7] A. Galani, V. Tsitsias, D. Stellas, V. Psycharis, C.P. Raptopoulou, A. Karaliota, J. Inorg. Biochem. 142 (2015) 109–117.
- [8] S. Treviño, D. Velázquez-Vázquez, E. Sánchez-Lara, A. Diaz-Fonseca, J.A. Flores-Hernandez, A. Pérez-Benítez, E. Brambila-Colombres, E. González-Vergara, Oxidative Med. Cell. Longev. 2016 (2016) 605870514 pages.
- [9] P.L. Pedersen, E. Carafoli, Trends Biochem. Sci. 12 (1987) 146–150.
- [10] C. Toyoshima, M. Nakasako, H. Nomura, H. Ogawa, Nature 405 (2000) 647–655.
- [11] L. Yatime, M.J. Buch-Pedersen, M. Musgaard, J.P. Morth, A.-M.L. Winther, B.P. Pedersen, C. Olesen, J.P. Andersen, B. Vilsen, B. Schiøtt, M.G. Palmgren, J.V. Møller, P. Nissen, N. Fedosova, Biochim. Biophys. Acta 1787 (2009) 207–220.
- [12] M. Aureliano, G. Fraqueza, C.A. Ohlin, Dalton Trans. 42 (2013) 11770–11777.
- [13] L.C. Cantley Jr., L. Josephson, R. Warner, M. Yanagisawa, C. Lechene, G. Guidotti, J. Biol. Chem. 252 (1977) 7421–7423.
- [14] M. Aureliano, D.C. Crans, J. Inorg. Biochem. 103 (2009) 536–546.
- [15] M.B. Čolović, D.V. Bajuk-Bogdanović, N.S. Avramović, I.D. Holclajtner-Antunović, N.S. Bošnjaković-Pavlović, V.M. Vasić, D.Z. Krstić, Bioorg. Med. Chem. 19 (2011) 7063–7069.

- [16] G. Fraqueza, C.A. Ohlin, W.H. Casey, M. Aureliano, J. Inorg. Biochem. 107 (2012) 82–89.
- [17] G. Fraqueza, L.A.E. Batista de Carvalho, M. Paula, M. Marques, L. Maia, C. André Ohlin, W.H. Casey, M. Aureliano, Dalton Trans. 41 (2012) 12749–12758.
- [18] H. Stephan, M. Kubeil, F. Emmerling, C.E. Müller, Eur. J. Inorg. Chem. 10–11 (2013) 1585–1594.
- [19] S.H. Saeed, R. Al-Oweini, A. Haider, U. Kortz, J. Iqbal, Toxicol. Rep. 1 (2014) 341–352.
- [20] S.Y. Lee, A. Fiene, W. Li, T. Hanck, K.A. Brylev, V.E. Fedorov, J. Lecka, A. Haider, H.J. Pietzsch, H. Zimmermann, J. Sévigny, U. Kortz, H. Stephan, C.E. Müller, Biochem. Pharmacol. 93 (2015) 171–181.
- [21] J. Iqbal, M. Barsukova-Stuckart, M. Ibrahim, S.U. Ali, A.A. Khan, U. Kortz, Med. Chem. Res. 22 (2013) 1224–1228.
- [22] N.I. Gumerova, L. Krivosudský, G. Fraqueza, J. Breibeck, E. Al-Sayed, E. Tanuhadi, A. Bijelic, J. Fuentes, M. Aureliano, A. Rompel, Metallomics 10 (2018) 287–295.
- [23] Bruker SAINT v8.37A & V7.68A Copyright © 2005–2018 Bruker AXS.
- [24] G.M. Sheldrick, SADABS, University of Göttingen, Germany, 1996.
- [25] O.V. Dolomanov, L.J. Bourhis, R.J. Gildea, J.A.K. Howard, H. Puschmann, J.: OLEX2: a complete structure solution, refinement and analysis program, J. Appl. Crystallogr. 42 (2009) 339–341.
- [26] C.B. Huebschle, G.M. Sheldrick, B. Dittrich, ShelXle: a Qt graphical user interface for SHELXL, J. Appl. Crystallogr. 44 (2011) 1281–1284.
- [27] G.M. Sheldrick, SHELXS v 2016/4, University of Göttingen, Germany, 2015.
- [28] G.M. Sheldrick, SHELXL v 2016/4, University of Göttingen, Germany, 2015.
- [29] A.L. Spek, Structure validation in chemical crystallography, Acta Cryst D65 (2009) 148–155.
- [30] Diamond - Crystal and Molecular Structure Visualization. Crystal Impact - Dr. H. Putz & Dr. K. Brandenburg GbR, Kreuzherrenstr. 102, 53227 Bonn, Germany. <http://www.crystalimpact.com/diamond>
- [31] R. Kato, A. Kobayashi, Y. Sasaki, Inorg. Chem. 21 (1982) 240–246.
- [32] K. Nomiya, K. Kato, M. Miwa, Polyhedron 5 (1986) 811–813.
- [33] S. Uematsu, Z. Quan, Y. Suganuma, N. Sonoyama, J. Power Sources 217 (2012) 13–20.
- [34] K.J. Karnaky Jr., K.J. Degnan, J.A. Zadunaisky, Science 195 (1977) 203–205.
- [35] J.A. Zadunaisky, The chloride cell: the active transport of chloride and the paracellular pathways, in: W.S. Hoar, D.J. Randall (Eds.), Fish Physiology, XB, Academic Press, New York, 1984, pp. 129–176.
- [36] J.A. Martos-Sitcha, G. Martínez-Rodríguez, J.M. Mancera, J. Fuentes, Comp. Biochem. Physiol. A Physiol. 182 (2015) 93–101.
- [37] E.V. Murashova, A.B. Iluikhin, N.N. Chudinova, Russ. J. Inorg. Chem. 46 (2001) 1292–1295.
- [38] I. Andersson, A. Gorzsás, C. Kerezi, I. Tóth, L. Pettersson, Dalton Trans. (2005) 3658–3666.
- [39] S. Hua, G. Inesi, C. Toyoshima, J. Biol. Chem. 275 (2000) 30546–30550.
- [40] R. Krulík, I. Farská, J. Prokeš, Neuropsychobiology 3 (1977) 129–134.
- [41] N. Bošnjaković-Pavlović, D. Bajuk-Bogdanović, J. Zakrzewska, Z. Yan, I. Holclajtner-Antunović, J.-M. Gillet, A. Spasojević-de Biré, J. Inorg. Biochem. 176 (2017) 90–99.
- [42] T. Tiago, P. Martel, C. Gutiérrez-Merino, M. Aureliano, Biochim. Biophys. Acta 1774 (2007) 474–480.
- [43] M.P.M. Marques, D. Gianolio, S. Ramos, L.A.E. Batista de Carvalho, M. Aureliano, Inorg. Chem. 56 (2017) 10893–10903.
- [44] A. Bijelic, A. Rompel, Coord. Chem. Rev. 299 (2015) 22–38.
- [45] A. Solé-Daura, V. Goovaerts, K. Stroobants, G. Absillis, P. Jiménez-Lozano, J.M. Poblet, J.D. Hirst, T.N. Parac-Vogt, J.J. Carbó, Chem. Eur. J. 22 (2016) 15280–15289.
- [46] M. Arefian, M. Mirzaei, H. Eshtiagh-Hosseini, A. Frontera, Dalton Trans. 46 (2017) 6812–6829.
- [47] A. Bijelic, M. Aureliano, A. Rompel, Chem. Commun. 54 (2018) 1153–1169.
- [48] A. Bijelic, M. Aureliano, A. Rompel, Angew. Chem. Int. Ed. 58 (2019) 2980–2999.
- [49] M. Aureliano, Oxidative Med. Cell. Longev. 2016 (2016) 61034578 pages.
- [50] A. Levina, D.C. Crans, P.A. Lay, Coord. Chem. Rev. 352 (2017) 473–498.
- [51] A. Levina, P.A. Lay, Chem. Asian J. 12 (2017) 1692–1699.
- [52] M. Le, O. Rathje, A. Levina, P.A. Lay, J. Biol. Inorg. Chem. 22 (2017) 663–672.
- [53] K.A. Doucette, K.N. Hassell, D.C. Crans, K.A. Doucette, J. Inorg. Biochem. 165 (2016) 56–70.
- [54] T. Jakusch, T. Kiss, Coord. Chem. Rev. 351 (2017) 118–126.
- [55] D. Sanna, V. Ugone, G. Micera, P. Buglyó, L. Bír, E. Garribba, Dalton Trans. 46 (2017) 8950–8967.
- [56] D. Sanna, J. Palomba, G. Lubinu, P. Buglyó, S. Nagy, F. Perdi, J. Med. Chem. 62 (2019) 654–664.
- [57] R. Prudent, V. Moucadet, B. Laudet, C. Barette, L. Lafanechère, B. Hasenknopf, J. Li, S. Barety, E. Lacôte, S. Thorimbert, M. Malacria, P. Gouzerh, C. Cochet, Chem. Biol. 15 (2008) 683–692.
- [58] M. Garner, J. Reglinski, W.E.J. McMurray, I. Abdullah, R. Wilson, J. Biol. Inorg. Chem. 2 (1997) 235–241.
- [59] T. C. Delgado, A. I. Tomaz, I. Correia, J. C. Pessoa, J.G. Jones, C.F. Galdes et al., J. Inorg. Biochem. 99 (2005) 2328–2339.
- [60] T. Jakusch, É.A. Enyedy, K. Kozma, Z. Paár, A. Bényei, T. Kiss, Inorg. Chim. Acta 420 (2014) 92–102.
- [61] D. Sanna, M. Serra, G. Micera, E. Garribba, Inorg. Chem. 53 (2014) 1449–1464.