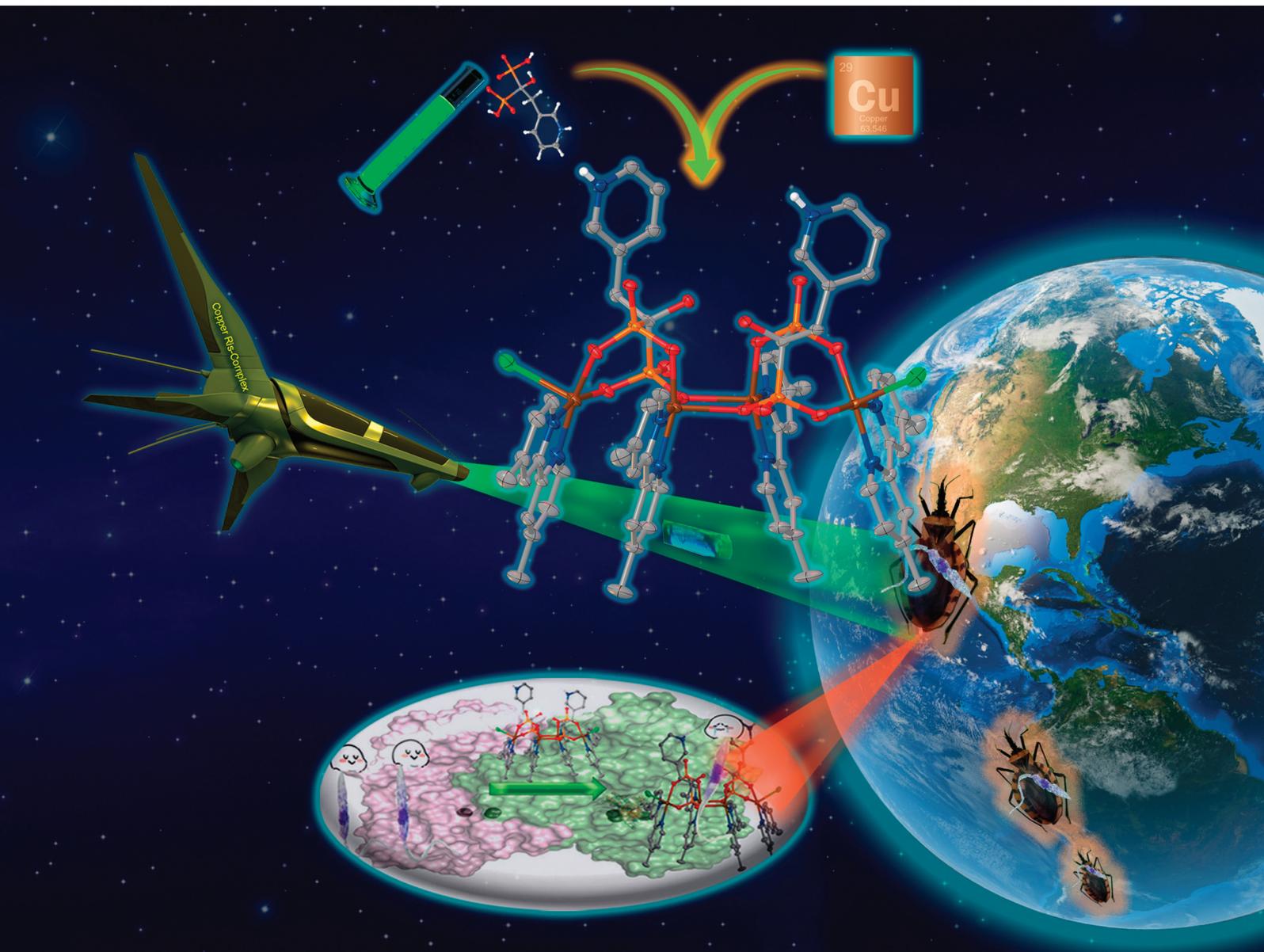


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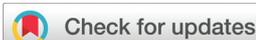
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**PAPER**

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# Tetranuclear and dinuclear Cu(II) complexes with risedronate as *anti-Trypanosoma cruzi* and *anti-Leishmania mexicana* agents. Synthesis, crystal structures, and biological evaluation†

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The development of new biometal-based complexes containing antiparasitic bioactive ligands is a central field of coordination chemistry that impacts bioinorganic, medicinal, and biological chemistry. Herein, two novel water-soluble polynuclear Cu(II)-complexes with formula  $[\text{Cu}_4(4,4'\text{-dmbp})_4(\mu_3\text{-HRis})_2\text{Cl}_2]$ , **1** and  $[\text{Cu}_2(5,5'\text{-dmbp})_2(\mu_2\text{-HRis})(\text{H}_2\text{O})\text{Cl}]$ , **2**, (4,4'-dmbp = 4,4'-dimethyl-2,2'-bipyridine, 5,5'-dmbp = 5,5'-dimethyl-2,2'-bipyridine, HRis = risedronate), were synthesized by self-assembly solution reactions between the corresponding precursor complexes  $[\text{Cu}_2(\text{dmbp})\text{Cl}_2]$  and the drug Na<sub>2</sub>Ris in aqueous media. Both Cu(II)-Ris complexes **1–2** were structurally described by single-crystal X-ray diffraction, characterized by spectroscopic tools (IR-ATR, HRMS, UV-Vis, EPR) and studied as antiparasitic agents against *Trypanosoma cruzi* causative agent of Chagas disease and *Leishmania mexicana* that is the etiological agent of cutaneous leishmaniasis. X-ray structural analysis reveals that **1** is an uncommon tetranuclear Cu<sub>4</sub> complex where four crystallographically independent units  $[\text{Cu}(4,4'\text{dmbp})]^{2+}$  are double-bridged coordinated by two tetra-deprotonated ligands HRis containing the protonated pyridine ring. All Cu(II) centers show a distorted square-based pyramid geometry, and they are coordinated by two bisphosphonate fragments from HRis in a coordination environment  $\mu_3$  for each one. Crystal analysis of **2** displays a dinuclear Cu<sub>2</sub> complex where one ligand HRis coordinated to two different units  $[\text{Cu}(4,4'\text{dmbp})]^{2+}$  in a  $\mu_2$  mode, both Cu(II) present distorted square-based pyramid geometry. In general, complexes **1–2** are hydrostable in the millimolar concentration range and present low cytotoxicity (<22% on the growth of cancer cell lines and healthy COS-7 cells) similar to the commercial drug, monosodium salt of risedronic acid (NaRis). Complexes **1–2** and NaRis were evaluated *in vitro* against *T. cruzi* epimastigotes and *L. mexicana* promastigotes. Results demonstrated that these Cu-Ris complexes improved the percentages of growth inhibition for *T. cruzi*. This inhibition ranged from 62–70% at concentrations of 5.0 mM after 24 h and 48 h incubation, compared to those observed for free, which has an inhibition of ~38%. Under the same concentration at 24 h incubation, complex **1** has a significantly greater inhibition effect against *L. mexicana* (63%) compared to free NaRis (50%). Reduction in parasite metabolisms and morphological changes included membrane damage, vacuolization, reduction of size and loss of flagellum were also observed. Importantly cytotoxicity to VERO cells was minor with the Cu(II)-Ris complexes compared with NaRis. The molecular docking analysis showed significant affinity towards the enzyme farnesyl diphosphate synthase from *T. cruzi* (TcFPPS), including simulations of the complexes Cu(II) at the TcFPPS binding site.

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†Electronic supplementary information (ESI) available: General information, X-ray crystallographic data, IR-ATR and EPR spectra for **1–2**, crystal packing diagrams of **1–2** and molecular docking depictions. CCDC 2329846 and 2396933. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d4dt03516j>



## Introduction

Chagas disease and leishmaniasis are diseases caused by the protozoan parasites *Trypanosoma cruzi* (*T. cruzi*) and *Leishmania* spp. that affect millions of humans around the world with high mortality and currently, they are associated with the drawbacks of used drugs such as severe side reactions and the emergence of resistance.<sup>1–4</sup> These medical conditions are considered neglected tropical diseases and a global challenge by the World Health Organization (WHO)<sup>5</sup> because cause serious public health problems in countries from Asia, Africa and Latin America.<sup>6</sup> It is known that these parasitic diseases can also affect non-endemic regions such as Europe and North America due to population mobility.<sup>7,8</sup>

In 2022, the WHO estimated that there are ~7 million people infected with the parasite *T. cruzi* and around 70 million presenting a high risk of acquiring it.<sup>9</sup> The estimated global incidence of leishmaniasis is ~12 million people<sup>6</sup> and a population at risk of around 350 million.<sup>10,11</sup> Infected flies transmit *Leishmania* spp. to human populations.<sup>12</sup> *Leishmania mexicana* (*L. mexicana*) is responsible for the endemic disease in México and Central America.<sup>13</sup>

While the need for novel efficient drugs with a low grade of toxicity is evident, currently the pharmacologic treatments are partially effective against the target parasites, and the vast majority produce considerable side reactions as well as, these available drugs for Chagas and leishmaniasis treatment are not recommended in persons with hepatic/renal impairment among other medical conditions.<sup>2,14,15</sup> Additionally, they induce the rise of resistant parasites.<sup>1</sup>

For Chagas disease (American Trypanosomiasis), only two commercial drugs are available, a 2-nitroimidazole-based, benznidazole and nitrofurantoin-based drug, nifurtimox have been used now for over 50 years.<sup>9,14,16</sup> Meanwhile, for leishmaniasis some Sb(v)-based complexes such as stibogluconate<sup>17</sup> and meglumine antimonate<sup>18</sup> have been clinically used in the first-line of the infection for decades.<sup>19</sup> Besides, alternative commercial antiprotozoal drugs such as liposomal amphotericin,<sup>20</sup> pentamidine<sup>21</sup> and paromomycin.<sup>22</sup>

In general, these pharmaceuticals are considerably toxic, require prolonged treatment, and are not very effective in the chronic stage of diseases mentioned.<sup>12,21,23</sup> For these reasons, the search for new drugs that have significant activity against these parasites without presenting serious side effects is a relevant field of research and an ongoing challenge. However, the creation of such drugs is not a trivial task and clearly, needs elaborate molecular strategy and synthetic approaches.

Typical searching efforts consist of finding novel bioactive compounds from natural sources.<sup>24,25</sup> Another emerging molecular strategy is the development of synthetic metal complexes bearing a ligand with proven antiparasitic activity (bioactive ligand).<sup>19,26–29</sup>

Recent reports in the context of medicinal inorganic chemistry have displayed that transition-metal coordination complexes may have multiple mechanisms of action by combining bioactive antiparasitic ligands (*e.g.* clotrimazole, ketoconazol,

*N*-acylhydrazones, aminoquinoxalines,  $\alpha$ -aminoacidates, poly-pyridyl ligands, nitrofuranyl-derivatives, (tio)semicarbazones, thiols, purines and glycosylated pyridines) with metal centers such as Ru(II),<sup>18,30</sup> Fe(III),<sup>31</sup> V(IV),<sup>32–34</sup> Cu(II),<sup>35,36</sup> Pd(II),<sup>37–39</sup> Pt(II)<sup>40,41</sup> and Au(I),<sup>42,43</sup> leading to synergistic/additive effects against *T. cruzi* and *Leishmania* spp.

On the other hand, bisphosphonate compounds are analogs of pyrophosphate ( $P_2O_7^{4-}$ ) anion where the central O atom is substituted by a C atom leading a rigid P–C–P backbone. This chemical change generates compounds more stable to hydrolysis and a great variety of functional groups on the C atom can be achieved. Among these compounds, risedronate (Ris; 1-hydroxy-2-(3-pyridinyl)-ethylidene-bisphosphonate) is a worldwide prescribed drug for osteoporosis and bone cancer therapy.<sup>44–46</sup> Interestingly, Ris can inhibit the proliferation of *T. cruzi* and *Leishmania* spp., both *in vitro* and *in vivo* without presenting toxicity to host cells.<sup>44,47,48</sup> In biochemical terms, Ris is able to inhibit the farnesyl pyrophosphate synthase (FPPS) which is an essential enzyme for trypanosomatid parasites and *Leishmania* promastigotes.<sup>3,47,49,50</sup> However, antiparasitic studies of transition-metal complexes with Ris still remain largely unexplored, probably due to metal-Ris complexes being typically limited to high-dimensional metal-organic networks, which are practically insoluble in aqueous media.<sup>51,52</sup> The literature features only one report of a series of metal complexes containing Ris with activity against Chagas disease.<sup>53</sup> These complexes ( $[M(Ris)_2]$ , M = Ni(II), Cu(II), Mn(II), Co(II)) were synthesized under strongly acidic conditions to achieve mononuclear species. One of the advantages of these metal complexes with Ris is that an improvement can be achieved in the pharmacokinetics of the complex in comparison with the free sodium salt of Ris because the coordination to a metal center modifying its solubility and lipophilicity.<sup>53</sup>

To the best of our knowledge, Cu(II)–Ris metal complexes have never been studied as *anti-Leishmania* agents. Taking this into account, we assumed that a potential drug for Chagas or leishmaniasis can be achieved by metal complexes containing a commercial drug already authorized by regulatory agencies (Ris) with a biometal such as Cu(II)<sup>35</sup> and an ancillary chelating ligand to get control of the coordination and geometry of the metal atom.

The results obtained for two novel hydrostable polynuclear Ris–Cu(II) complexes bearing two different dimethyl-2,2'-bipyridyl ligands including synthesis, X-ray structural analysis, spectroscopic studies, antiproliferative effect on *T. cruzi* epimastigotes and *L. mexicana* promastigotes, cytotoxic activity and molecular docking calculations are summarized below. In this work, biological results are compared to those obtained with NaRis for *T. cruzi* and *L. mexicana*.

## Results and discussion

### Synthesis and crystal structures

Ris-based transition-metal complexes are often supramolecular metal-organic frameworks because the bisphosphonate



fragment is a potent complexing agent with multiple coordination sites. These metal organophosphate compounds have been used in magnetism,<sup>52,54</sup> fluorescent properties,<sup>55</sup> structural topologies<sup>56,57</sup> and antibacterial studies.<sup>51</sup> However, anti-parasitic studies in aqueous media are practically unexplored.

In order to further investigate this chemistry of Cu(II) with the commercial drug Ris and explore for potential *anti-Chagas/Leishmania* applications of such compounds, we synthesized two novel Cu(II)–Ris complexes **1–2** based on the reaction of Cu(II)–2,2′-bipyridine compounds: [Cu<sub>2</sub>(4,4′-dmbp)<sub>2</sub>Cl<sub>4</sub>] or [Cu<sub>2</sub>(5,5′-dmbp)<sub>2</sub>Cl<sub>4</sub>] (4,4′-dmbp = 4,4′-dimethyl-2,2′-bipyridine and 5,5′-dmbp = 5,5′-dimethyl-2,2′-bipyridine) with Na<sub>2</sub>Ris in water in a 1 : 1 molar ratio. We chose bipyridines as co-ligands to (1) control the structure around the Cu(II), (2) favor square pyramid geometry<sup>58</sup> and (3) avoid the formation of infinite networks which are insoluble in physiological media. Crystals of **1–2** were grown directly from the reaction mixture by slow evaporation after 1 week and were characterized by single crystal structure determination. The synthesis path and chemical structures of **1–2** are shown in Scheme 1.

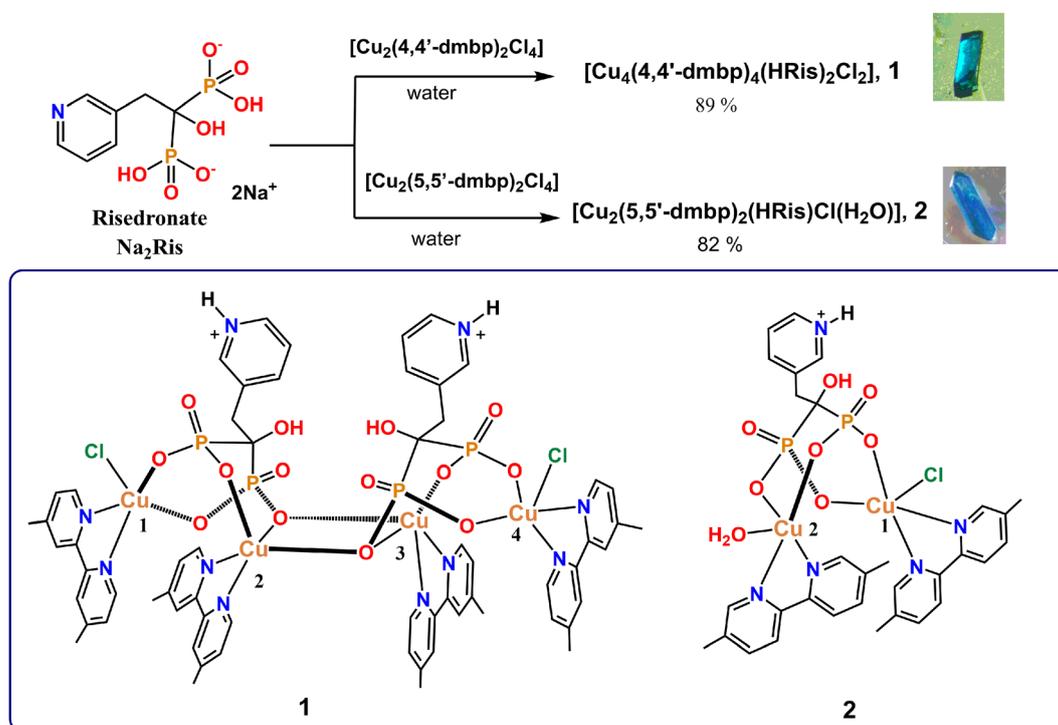
Tables S1–S5 in the ESI† contain crystallographic data, select distances, and angles around metal centers in addition to H-bonds within the crystal packing of these complexes.

**Crystal structure of 1.** Fig. 1A shows a perspective view of the crystal structure of **1** with atomic numbering around the metallic core. Crystallographic analysis reveals that **1** is a tetranuclear Cu<sub>4</sub> complex comprised of two dinuclear [Cu<sub>2</sub>(4,4′-dmbp)<sub>2</sub>(μ<sub>3</sub>-HRis)Cl] units bridging by two tetra-deprotonated

bisphosphonate groups {O<sub>3</sub>PC(OH)(CH<sub>2</sub>-3-C<sub>5</sub>NH<sub>5</sub>)PO<sub>3</sub>} (see Fig. 1) of two different HRis ligands. The pyridine rings of each Ris ligand are protonated (HRis) and the central C-OH groups remain protonated, resulting in an overall charge of 2+, which is balanced by two Cl<sup>−</sup> ions coordinated to two terminal Cu(II) centers. The coordination mode of the two HRis ligands is similar, each tetra-deprotonated ligand HRis acts as tetra-dentate chelate ligand, connecting three Cu(II) atoms through different four O atoms from bisphosphonate moiety in a coordination environment of μ<sub>3</sub>,η<sup>4</sup>-O,O′,O′′,O′′′.<sup>56,59</sup> An individual structural analysis of the phosphonate {C-PO(O<sup>−</sup>)<sub>2</sub>} groups, reveals that one phosphonate moiety coordinates two Cu(II) atoms through two different O atoms (bis(monodentate)-type) and the second one phosphonate group involves the coordination of one O atom to Cu(II) atom together the one μ<sub>2</sub>-O bridged-type coordination to two Cu(II) atoms (see Fig. S1†). Such coordination mode is still rare in the literature for bisphosphonates with transition metal ions.<sup>56</sup>

On the other hand, the four Cu(II) atoms inside **1** are crystallographically independent. In geometric terms, the four Cu(II) atoms form the vertices of a parallelogram which are linked through a double bisphosphonate bridge (Fig. 1B) with internal distances Cu1...Cu2, Cu2...Cu3 and Cu3...Cu4 varying from 3.2073(6) to 3.4509(7) Å, see Table 1. In this line, similar geometric parallelogram array was reported to a tetranuclear complex with formula [Cu<sub>4</sub>(μ<sub>4</sub>-PO<sub>4</sub>)<sub>2</sub>(μ<sub>2</sub>-CO<sub>3</sub>)].<sup>60</sup>

The short internuclear Cu...Cu distances in **1** strongly suggest that the tetranuclear Cu<sub>4</sub> core should present magnetic interactions similar to other tetranuclear Cu(II)-complexes



**Scheme 1** Chemical synthesis of Cu(II)–Ris complexes **1–2** (solvent molecules are excluded).



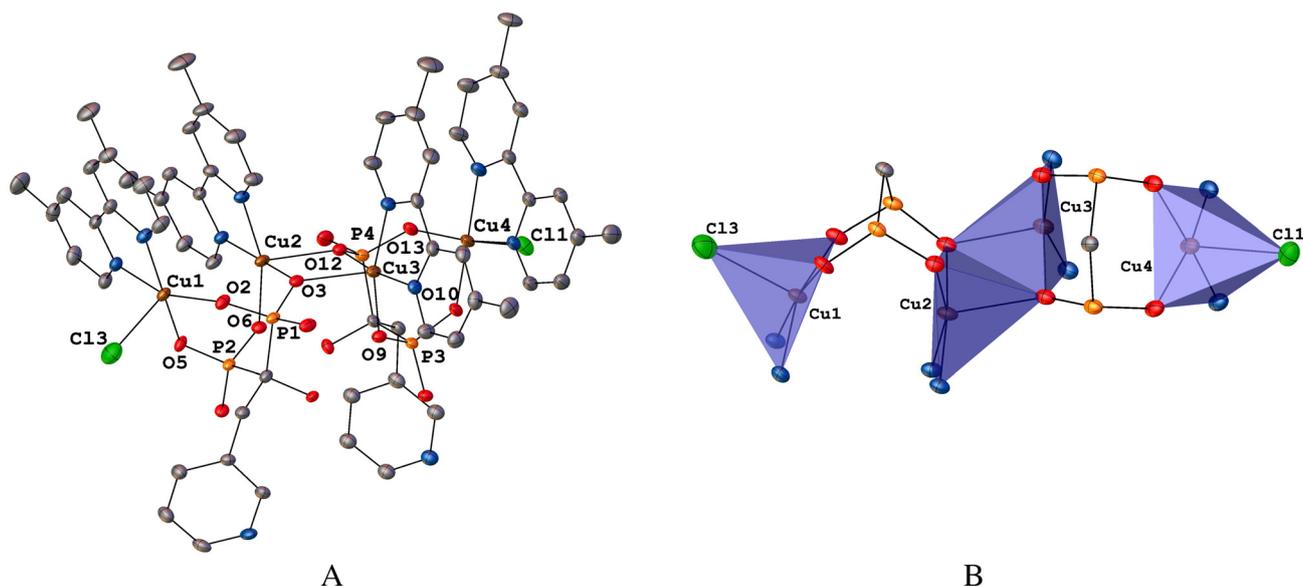


Fig. 1 (A) ORTEP diagram at 40% probability of **1**. Hydrogen atoms and solvent molecules were omitted for clarity. (B) Combined ORTEP/polyhedral representation of the  $\text{Cu}_4$  core from **1**.

Table 1 Cu...Cu distances (Å) inside crystal structures of complexes **1** and **2**

Complex	Atoms	Distance (Å)
<b>1</b>	Cu1...Cu2	3.4509(7)
	Cu2...Cu3	3.2073(6)
	Cu3...Cu4	3.4077(7)
	Cu1...Cu4	8.9777(5)
<b>2</b>	Cu1...Cu2	3.4695(4)

built with phosphate anions in bridge  $\mu_3$ -phosphonate/phosphate coordination mode.<sup>59–61</sup>

In general, all Cu(II) atoms have a coordination number CN = 5 and distorted square pyramidal geometries (Fig. 1B). Their Addison trigonality index ( $\tau$ ) are less than 0.19, (Table S6†) which is consistent with this type of coordination geometry.<sup>62</sup> The value of  $\tau$  is zero for an ideal square pyramid with  $C_{4v}$  symmetry, while  $\tau = 1$  for an ideal trigonal bipyramid with  $D_{3h}$  symmetry ( $\tau = (\alpha - \beta)/60$ , where  $\alpha$  and  $\beta$  correspond to the two largest angles).<sup>62</sup>

In the axial positions, Cu1 and Cu4 have occupational disorders between Cl atoms and water molecules. For Cu1 atom, the occupational ratio is 27/73 (Cl3/H<sub>2</sub>O) while for Cu4 atom is 40/60 (Cl1/H<sub>2</sub>O). For these Cu atoms,  $\tau$  values were estimated considering the coordinated Cl atoms. The four Cu(II) centers are slightly above the mean basal plane as is shown in the polyhedral representations in Fig. 1B.

The two terminal Cu1 and Cu4 atoms present a similar [CuN<sub>2</sub>O<sub>2</sub>Cl] coordination sphere where two N atoms of 4,4'-dmbp and two O atoms of different O–P fragments of the bisphosphonate (P1/P2 for Cu1 and P3/P4 for Cu4) are co-

ordinated in the basal position, and a Cl<sup>−</sup> atom (Cu1–Cl3 and Cu4–Cl1) is positioned in the apical site.

The central Cu2 and Cu3 atoms are double-bridged by two O atoms ( $\mu_2$ -O3 and  $\mu_2$ -O12) from two different bisphosphonate fragments forming a tight four-membered ring {Cu2– $\mu_2$ (O3)– $\mu_2$ (O12)–Cu3} where all atoms are practically coplanar (Fig. S2†) with angles Cu2–O–Cu3,  $\angle = 97.46^\circ$ – $98.80^\circ$  and O3–Cu–O12,  $\angle = 81.81^\circ$ – $81.92^\circ$ .

Both internal Cu(II) atoms contain a [CuN<sub>2</sub>O<sub>3</sub>] coordination sphere where two N atoms of 4,4'-dmbp and two O of different O–P fragments (P1 and P4) are coordinated in the basal positions and the apical position is occupied by an O atom of one of the bridging bisphosphonate moieties with bond lengths, Cu2...O12–P4, 2.258(2) and Cu3...O3–P1, 2.236(2) Å, significantly longer than the basal plane ones, which generates a square-based pyramid elongated over the apical position.<sup>63</sup>

The 4,4'-dmbp ligands participate in intramolecular slightly offset  $\pi$ – $\pi$  stacking interactions with distances centroid...centroid in the range 3.728(7) Å–3.804(5) Å (Fig. S3†) and dihedral angles of  $\sim 5^\circ$ . The crystalline net is stabilized by multiple O–H...O and N–H...O hydrogen bonds formed by central C–OH groups, pyridinium fragments and the phosphonate groups (Table S4†).

**Crystal structure of 2.** X-ray analysis displays that the structure of **2** is a discrete dinuclear species with a general formula [Cu<sub>2</sub>(5,5'-dmbp)<sub>2</sub>( $\mu_2$ -HRis)(H<sub>2</sub>O)Cl], (Fig. 2A) containing two crystallographically independent Cu(II) atoms in slightly distorted square pyramidal geometry ( $\tau$  values of 0.19 and 0.21 for Cu1 and Cu2, respectively Table S6†). In **2**, the ligand HRis chelates two Cu(II) atoms through four phosphonate O atoms (O1, O2, O4 and O5), thus, each phosphonate group is in  $\mu_2$ -O, O' bridging mode (Fig. S1†).<sup>59</sup> Ris has its typical zwitterionic character, with a positive charge at protonated pyridine.



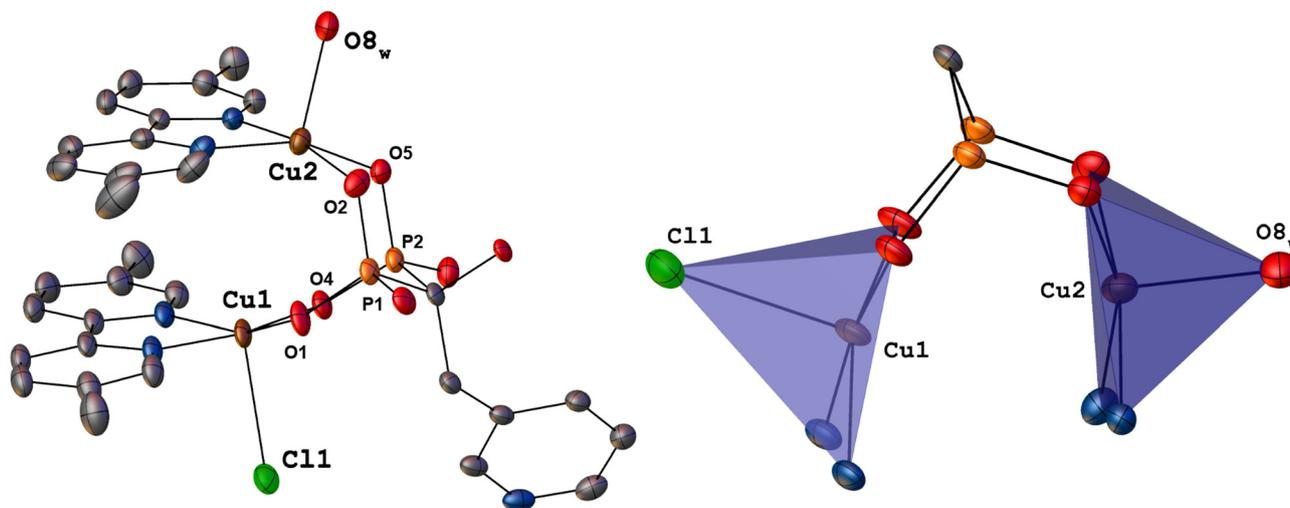


Fig. 2 (A) ORTEP diagram at 40% probability of **2**. Hydrogen atoms and solvent molecules were omitted for clarity. (B) Combined ORTEP/polyhedral representation of the  $\text{Cu}_2$  core from **2**.

A similar bisphosphonate coordination mode has been described in a dinuclear  $\text{Cu(II)}$ -zoledronate complex.<sup>64</sup>

For both  $\text{Cu(II)}$  atoms, 5,5'-dmbp provides a bidentate  $\text{N}_2$  coordination mode and the other two positions of the basal plane are occupied by two O atoms of a bridging bisphosphonate fragment. The apical sites are occupied by one Cl atom ( $\text{Cu1-Cl1}$ , 2.5341(7) Å) and one water molecule ( $\text{Cu2-O8}$ , 2.066(5) Å). The  $\text{Cu1}\cdots\text{Cu2}$  distance, 3.4695(4) Å, varies marginally from that found in **1** (Table 1).

In this instance, 5,5'-dmbp also forms offset  $\pi$ - $\pi$  interactions with a separation of centroid $\cdots$ centroid ranging from 3.649(7) Å–3.683(4) Å, Fig. S4.† Furthermore, intermolecular O–H $\cdots$ O hydrogen bonds between C–OH groups grow the crystal packing (Table S5†).

#### HRMS, IR-ATR, UV-Vis and EPR characterization

$\text{Cu(II)}$ -Ris complexes **1–2** were isolated as pure crystalline samples according to high-resolution electrospray mass spectrometry (ESI-HRMS), elemental analysis (C, H, N), IR-ATR, UV-Vis and EPR.

One charged state for **1** at 774.036804  $m/z$  and for **2** at 774.037583  $m/z$  corresponding to monocationic dinuclear species  $[\text{Cu}_2(4,4'\text{-dmbp})_2(\text{HRis})]^+$  and  $[\text{Cu}_2(5,5'\text{-dmbp})_2(\text{HRis})]$ , respectively, are clearly observed by a positive scan. The signals in both complexes, separated by 1.0 unit, were isotopically resolved and matched very well the theoretical isotopically distribution (Fig. 3A and B); in addition, the multiplicities fit well with the presence of two  $\text{Cu(II)}$  atoms for each analysis.

The compiled infrared spectra of the salt NaRis and their related  $\text{Cu(II)}$ -Ris complexes **1–2** are illustrated in Fig. S5.† In the IR spectrum of NaRis, the stretching vibration band assigned to the hydroxyl group of the quaternary carbon (C–OH) appears at 3336  $\text{cm}^{-1}$ .<sup>65</sup> In cases of complexes **1** and **2**, this signal is strongly widened and shifted at 3372 and 3375  $\text{cm}^{-1}$ , respectively. This shift can be attributed to the

presence of intra/inter-molecular hydrogen bonds of type O–H $\cdots$ O between two different hydroxyl groups as observed in their crystal structures (see *supra*). Additionally, crystal structures of **1–2** are species with a high degree of hydration, thus, the broad bands centered at approximately 3380  $\text{cm}^{-1}$  can be assigned to overlapped stretching frequencies of –OH groups from multiple water molecules of crystallization with the C–OH group from Ris.<sup>63</sup>

In the 1100–1250  $\text{cm}^{-1}$  range, symmetric and asymmetric stretching bands of phosphonate  $\{\text{C-PO}(\text{O}^-)_2\}$  groups from Ris are observed.<sup>53,65</sup> The IR spectra of **1–2** are grossly similar in this region when allowance is made for the different coordinated ligands (Ris and dimethyl-2,2'-bipys). The most significant difference is a shifted ( $\Delta\nu = 8\text{--}22 \text{ cm}^{-1}$ ) to higher wavenumbers of P–O stretching bands of complexes **1–2** in comparison to NaRis which is consistent with coordination of phosphonate groups.<sup>53</sup>

Crystal structures of **1** and **2** show a high degree of hydration around the polynuclear cores which suggest that these complexes are hydrostable in solid-state. Considering that the hydrostability in solution is a key physicochemical property of biological interest in design of drugs, we verified the chemical stability of **1** and **2** in neutral water.

Complexes **1** and **2** can be dissolved in pure water in the millimolar concentration range (<10 mM) and, in general, these aqueous solutions are very stable for a couple of days, which was determined from their UV-Vis spectra corresponding to the fresh solutions, and measurements at different hours up to 48 h as is shown in Fig. S6 and S7.†

For both complexes, the absorption maxima in the visible region ( $\lambda_{\text{max}} = 646 \text{ nm}$  for **1** and  $\lambda_{\text{max}} = 643 \text{ nm}$  for **2**) practically do not present changes in this period of time.

On the other hand, the lipophilicity of metallodrugs is an important parameter involved in the cellular uptake;<sup>66</sup> thus, the partition coefficients between *n*-octanol and water



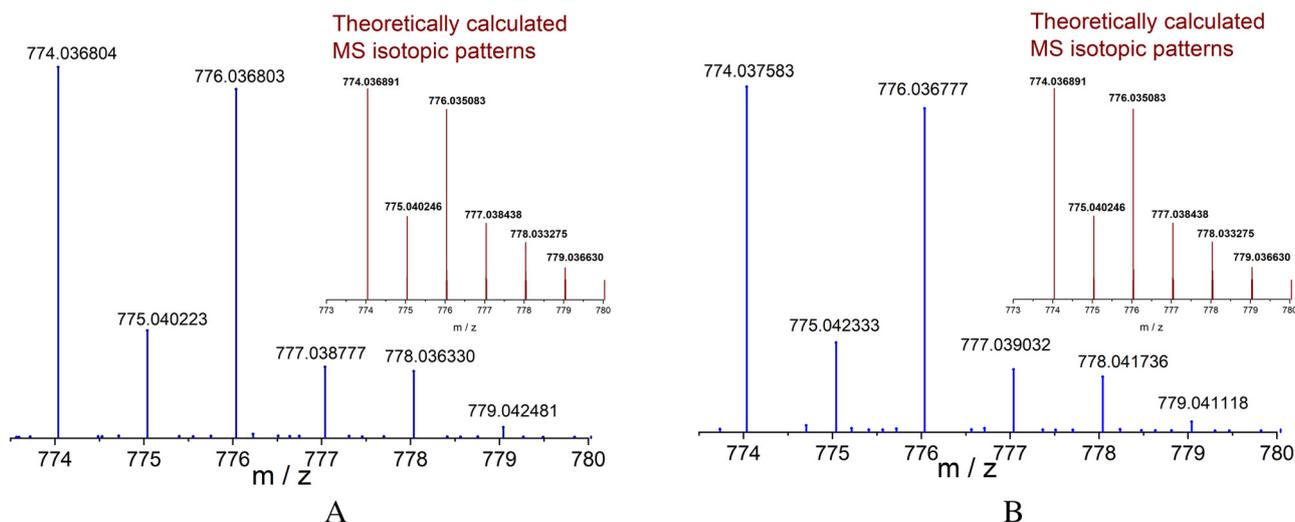


Fig. 3 HRMS-ESI spectra obtained by the positive scan of **1** (A) and **2** (B) in CH<sub>3</sub>OH–water (1 : 1, v/v). Insets: calculated isotopic distribution for monocationic dinuclear complexes: [Cu<sub>2</sub>(4,4'-dmbp)<sub>2</sub>(HRis)]<sup>+</sup> and [Cu<sub>2</sub>(5,5'-dmbp)<sub>2</sub>(HRis)]<sup>+</sup>.

( $\log P_{o/w}$ ) were estimated for complexes **1–2** (see Fig S8 and ESI<sup>†</sup>).

Both complexes showed greater affinity for the aqueous phase (complex **1**,  $\log P_{o/w} = -1.31 \pm 0.12$  and complex **2**,  $\log P_{o/w} = -1.26 \pm 0.08$ ), these values are not unexpected, due to the ionic character of the complexes and the high hydration energy of the Cl<sup>−</sup> counterions ( $\Delta G^\circ = -345 \text{ kJ mol}^{-1}$ ).<sup>67</sup>

Taking into account the short distances between Cu(II) atoms inside crystal structures of **1–2**, we recorded the EPR spectra in water frozen at 77 K (Fig. S9<sup>†</sup>).

EPR spectra are similar, exhibiting the characteristic signals of an  $S = 1$  effective spin system that contains two signals centered at 300 mT corresponding to  $\Delta M_S = \pm 1$  transitions.<sup>68</sup> These signals have a perpendicular component ( $D_\perp$ ) with a separation of  $\sim 50$  mT and a parallel component ( $D_\parallel$ ) with separation of  $\sim 100$  mT. For both complexes the signal due to the “forbidden” half-field  $\Delta M_S = \pm 2$  transition can be observed centered at 150 mT which confirmed the formation of dimer Cu<sub>2</sub> cores.

For complex **1**  $g_\parallel = 2.2400$  and  $g_\perp = 2.0946$  and for complex **2**  $g_\parallel = 2.2325$  and  $g_\perp = 2.0915$ .

On the half-field signal and the low-field parallel component of the spectra, a seven-line hyperfine structure with an intensity ratio 1 : 2 : 3 : 4 : 3 : 2 : 1 can be observed. Also, the hyperfine structure can be observed (insets, Fig. S9<sup>†</sup>) in 120–280 mT region of the spectra taken at higher gain. This seven-line hyperfine structure corresponds to the coupling of an unpaired spin with two Cu(II) centers with  $I = 3/2$ . Interestingly, there are very few examples in the literature of dinuclear Cu(II) complexes with similar magnetic properties.<sup>68,69</sup>

### Bioassays on cancer cellular lines

It has been noted that some characteristics of the metabolism of trypanosomatids and cancer cells share some similarities,

namely inefficient mitochondria systems that promote a high rate of aerobic glycolysis, among others.<sup>70</sup> There have also been studies that have shown that metal–ligand complexes containing polypyridyl DNA-intercalating ligands have activity against *L. mexicana* and *T. cruzi*.<sup>71</sup> Therefore, it is probable that antineoplastic moieties can also have anti-trypanosomatid activity. More recently, heteroleptic oxovanadium(IV) complexes containing polypyridyl ligands and Schiff bases have been evaluated against *T. cruzi* and against three cancer cell lines.<sup>72</sup>

Next, we have evaluated complexes **1–2** inhibitory activity on six cancer cell lines (glioblastoma, prostate, leukemia, colon, breast and lung) and on healthy COS-7 cells, Table 2 shows the growth inhibition studies on these cancer cell lines and on COS-7 at 1.0  $\mu\text{M}$  concentration. Interestingly for our proposals, complex **2** presents a slightly lower inhibition to healthy cells COS-7 (7.4%) compared to the value of inhibition (9.59%) shown by the commercial drug NaRis.

### Bioassays on *T. cruzi* and *L. mexicana*

The growth inhibition of epimastigotes of *T. cruzi* was evaluated with complexes **1–2** and compared with NaRis. As shown in Fig. 4, *T. cruzi* proliferation was reduced with all three compounds compared to untreated control parasites cultured in LIT medium at the first 24 h of exposure (Fig. 4A and B). In general, complexes **1** and **2** were more active against this form of parasite than the free NaRis at the evaluated concentrations of 0.5, 1.0, and 5.0  $\mu\text{M}$ . Complex **1** at 5.0  $\mu\text{M}$  produced the maximum inhibitory effect. Next, the IC<sub>50</sub> values were determined: **1** and **2** had an IC<sub>50</sub> of  $1.17 \pm 0.09 \mu\text{M}$  and  $0.73 \pm 0.14 \mu\text{M}$ , respectively, resulting in lower concentrations than NaRis control which had an IC<sub>50</sub> greater than 5.0  $\mu\text{M}$ .

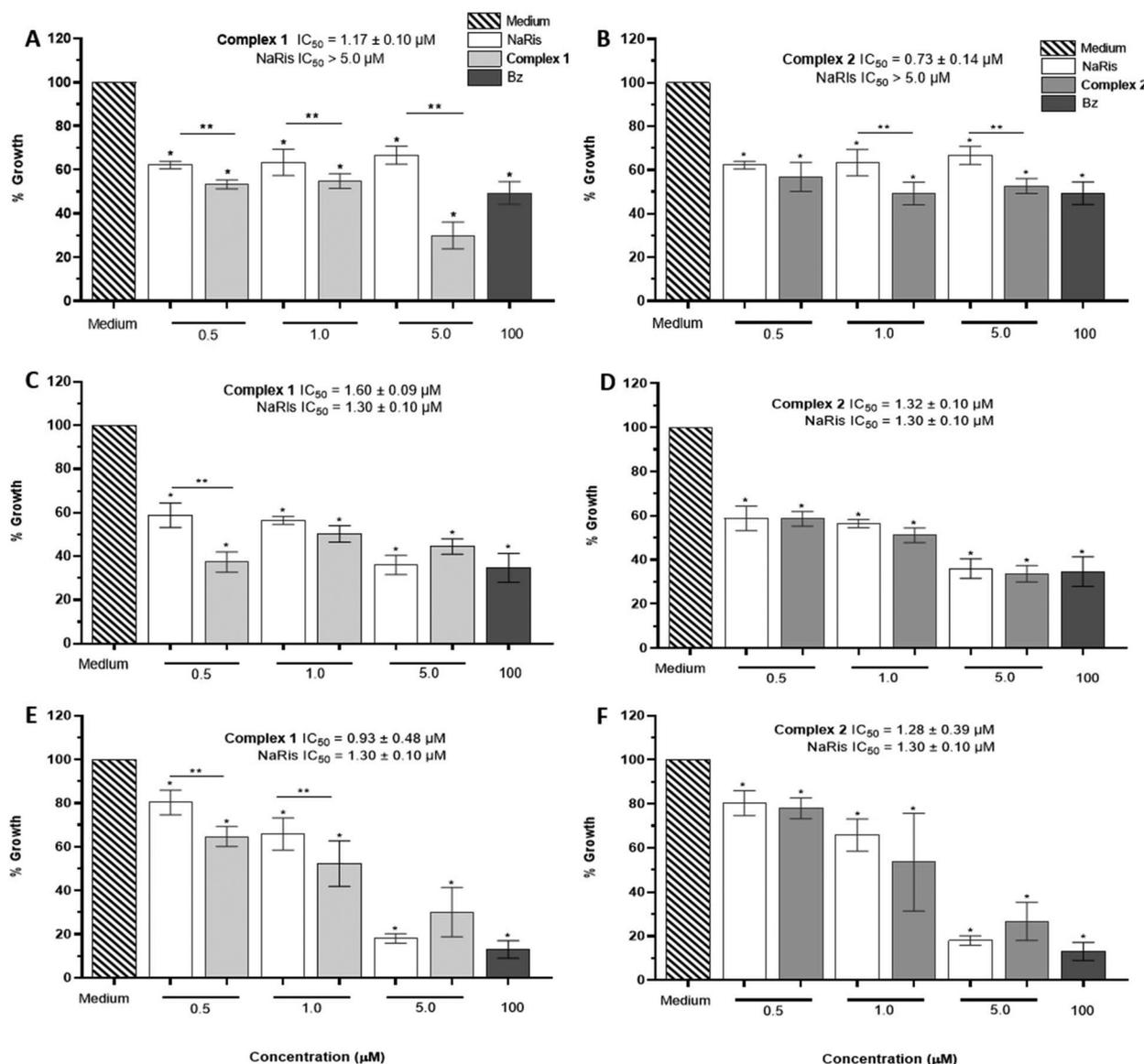
In addition, after 48 h of incubation with the compounds, there was also a general decrease in proliferation. Significant differences between NaRis and **1** were found at 0.5  $\mu\text{M}$ . The IC<sub>50</sub> of the three compounds were similar  $1.30 \pm 0.10 \mu\text{M}$



**Table 2** Effects of NaRis and complexes 1–2 on the growth of cancer cell lines and on healthy COS-7 cells

Compound [1.0 $\mu\text{M}$ ]	% of growth inhibition						
	U-251	PC-3	K-562	HCT-15	MCF-7	SKLU-1	COS-7
NaRis	NC	14.94	1.56	NC	NC	0.34	9.59
1	3.45	NC	10.12	NC	14.15	14.42	22.00
2	NC	NC	2.48	5.54	1.55	NC	7.44

U-251 = human glioblastoma, PC-3 = human prostate, K-562 = leukemia, HCT-15 = human colon, MCF-7 = human breast, SKLU-1 = human lung, COS-7 = monkey liver (non-cancerous). NC: non-cytotoxic.



**Fig. 4** Effect of complexes 1 and 2 on the growth of *T. cruzi* Gro strain epimastigotes. Parasite culture ( $4 \times 10^5$  parasites in 200  $\mu\text{L}$ ) were incubated with 0.5, 1.0 and 5.0  $\mu\text{M}$  of NaRis, complexes 1 and 2. Beznidazole (Bz, 100  $\mu\text{M}$ ) and medium were used as controls. Growth was evaluated at 24 h (A and B), 48 h (C and D) and 72 h (E and F). The number of parasites after treatment was established by counting in a Neubauer chamber, using a Microstar IV microscope (Reichert, USA). The results are presented as the average percent  $\pm$  the standard deviation of growth, from three independent experiments by duplicate. Ordinary one-way ANOVA was used for statistical analysis. The asterisk (\*) represents the statistically significant differences between the treatments compared to the control untreated parasite (medium) ( $p < 0.05$ ). (\*\*) asterisks represent the statistically significant differences between the treatments with NaRis with respect to treatments with complex 1 or complex 2 ( $p < 0.0001$ ).



(NaRis),  $1.60 \pm 0.09 \mu\text{M}$  (complex 1) and  $1.32 \pm 0.10 \mu\text{M}$  (complex 2) (Fig. 4C and D).

After 72 h of exposure, a progressive reduction in the growth of the treated parasites existed, achieving the best effect for the three compounds at the highest tested concentration of  $5.0 \mu\text{M}$  (Fig. 4E and F).

There were significant differences between the 0.5 and 1.0  $\mu\text{M}$  activities of 1 and NaRis, nevertheless,  $\text{IC}_{50}$  values of the three compounds (NaRis:  $1.30 \pm 0.10 \mu\text{M}$ , complex 1:  $0.93 \pm 0.48 \mu\text{M}$ , complex 2:  $1.28 \pm 0.39 \mu\text{M}$ ) were similar. It is worth mentioning that when comparing the commercially available drug to treat Chagas disease (benznidazole) there was an inhibition percentage of more than 50% but using a concentration of 100  $\mu\text{M}$ , which makes both complexes 1 and 2 very effective at a lower concentration.

In the case of promastigotes from *L. mexicana*, compounds 1 and 2 at concentrations 0.5, 1.0, and 5.0  $\mu\text{M}$  at the three different times mentioned before were also tested. In this case, at 24 h, the inhibition was better with NaRis at 0.5, 1.0, and 5.0  $\mu\text{M}$ , except for 1 at 5.0  $\mu\text{M}$  with  $65.17 \pm 3.43\%$  of growth inhibition. In general, only at the highest concentration tested were the Cu(II) compounds more effective. The calculated  $\text{IC}_{50}$  were complex 1,  $1.72 \pm 0.07 \mu\text{M}$  and complex 2,  $2.39 \pm 0.10 \mu\text{M}$ , these concentrations are lower than the  $\text{IC}_{50}$  for the drug NaRis (Fig. 5A and B).

Interestingly, after 48 h of exposure to both Cu(II)-compounds, it was observed that they were more effective than NaRis at all concentrations used. In the case of *L. mexicana* the mean inhibitory concentration turned out to be less than 0.50  $\mu\text{M}$  for complex 1 and  $0.52 \pm 0.04 \mu\text{M}$  for complex 2, while the  $\text{IC}_{50}$  of NaRis was  $1.77 \pm 0.10 \mu\text{M}$  (Fig. 5C and D). When analyzing the results in the maximum time evaluated (72 h), the growth percentage values varied irregularly concerning the concentration of the compounds. Only a more significant inhibition was observed at the highest concentrations with the Cu(II) compounds compared with NaRis. However, the calculated  $\text{IC}_{50}$  was similar for the three compounds (Fig. 5E and F).

On the other hand, we evaluated the metabolic activity of the parasites after incubation with NaRis and complexes 1 and 2 at 48 h using the MTT assay. Complexes 1 and 2 decreased the percentage of metabolic activity gradually with the increase in the concentration of the compound (data not shown), obtaining for *L. mexicana*  $\text{IC}_{50}$  of  $5.31 \pm 0.03 \mu\text{M}$  and  $3.97 \pm 0.18 \mu\text{M}$  for complexes 1 and 2, respectively. With *T. cruzi* the  $\text{IC}_{50}$  value for complex 1 was like that obtained with *L. mexicana*. For NaRis the  $\text{IC}_{50}$  were not reached at the maximum concentration testes (7.6 and 7.0  $\mu\text{M}$ ) (Table 3).

To evaluate the morphological damage on parasites, different concentrations of the compounds 1–2 were tested (data not shown), including the  $\text{IC}_{50}$  calculated by the MTT assays. Parasites were compared with those incubated with medium (Fig. 6A–D). For *T. cruzi* epimastigote the observed cellular alterations were cell membrane damage, vacuolization, loss of flagellum, and smaller size with complex 1 (5.0  $\mu\text{M}$ ) and complex 2 (3.6  $\mu\text{M}$ ), (Fig. 6B and C). For *L. mexicana*,

similar damages were observed for complex 1 (5.0  $\mu\text{M}$ ) and complex 2 (3.0  $\mu\text{M}$ ) (Fig. 6E and F).

A previous work has reported the use of a related risedronate complex with formula  $[\text{Cu}(\text{Ris})_2]$ , however, in that work the percentage of growth inhibition obtained on *T. cruzi* epimastigotes turned out to be only of 16% with a concentration at 25  $\mu\text{M}$ .<sup>53</sup>

Metal-free Ris has been previously tested in several parasitological studies which have demonstrated intracellular inhibition for *Toxoplasma gondii* of 70% with an  $\text{IC}_{50}$  of 95  $\mu\text{M}$  after 19 h of treatment.<sup>73</sup>

In this line, Garzoni used Ris to inhibit the proliferation of epimastigotes of the Y and EP strains of *T. cruzi*, at concentrations of 25  $\mu\text{M}$  to 400  $\mu\text{M}$ , obtaining  $\text{IC}_{50}$  values of 30.3  $\mu\text{M}$  and 26.4  $\mu\text{M}$ , respectively.<sup>74</sup>

Therefore, the results of the present work are promising because using lower concentrations was possible to inhibit the growth, metabolic activity and produce cell damage of *T. cruzi* and *L. mexicana*.

Taking into account that the lowest inhibitory concentration of parasite proliferation and the shortest exposure time to the compound are sought, it can be said that both Cu(II)-complexes 1–2 are more efficient than drug NaRis.

### Molecular docking

The farnesyl diphosphate synthase of *T. cruzi* (TcFPPS) is a homodimeric Mg(II) dependent enzyme (Fig. S10†), for molecular docking we use the crystal reported in the protein data bank with accession number 1YHM, we analyze the interactions of Cu(II)-Ris complexes 1 and 2 with the enzyme. It has been reported to have two highly conserved aspartate-rich motifs named the first aspartate-rich motif (FARM) and second aspartate-rich motif (SARM) located at opposite sides of the active site.<sup>44,75,76</sup> The interaction with amino acid residue ARG 107 (R107), GLN 247 (Q247), LYS 264 (K264) and LYS 207 (K207) stabilizes the binding between the enzyme and Ris (Fig. S11 and S12†) with a binding energy of  $\Delta G = -8.1 \text{ kcal mol}^{-1}$ .

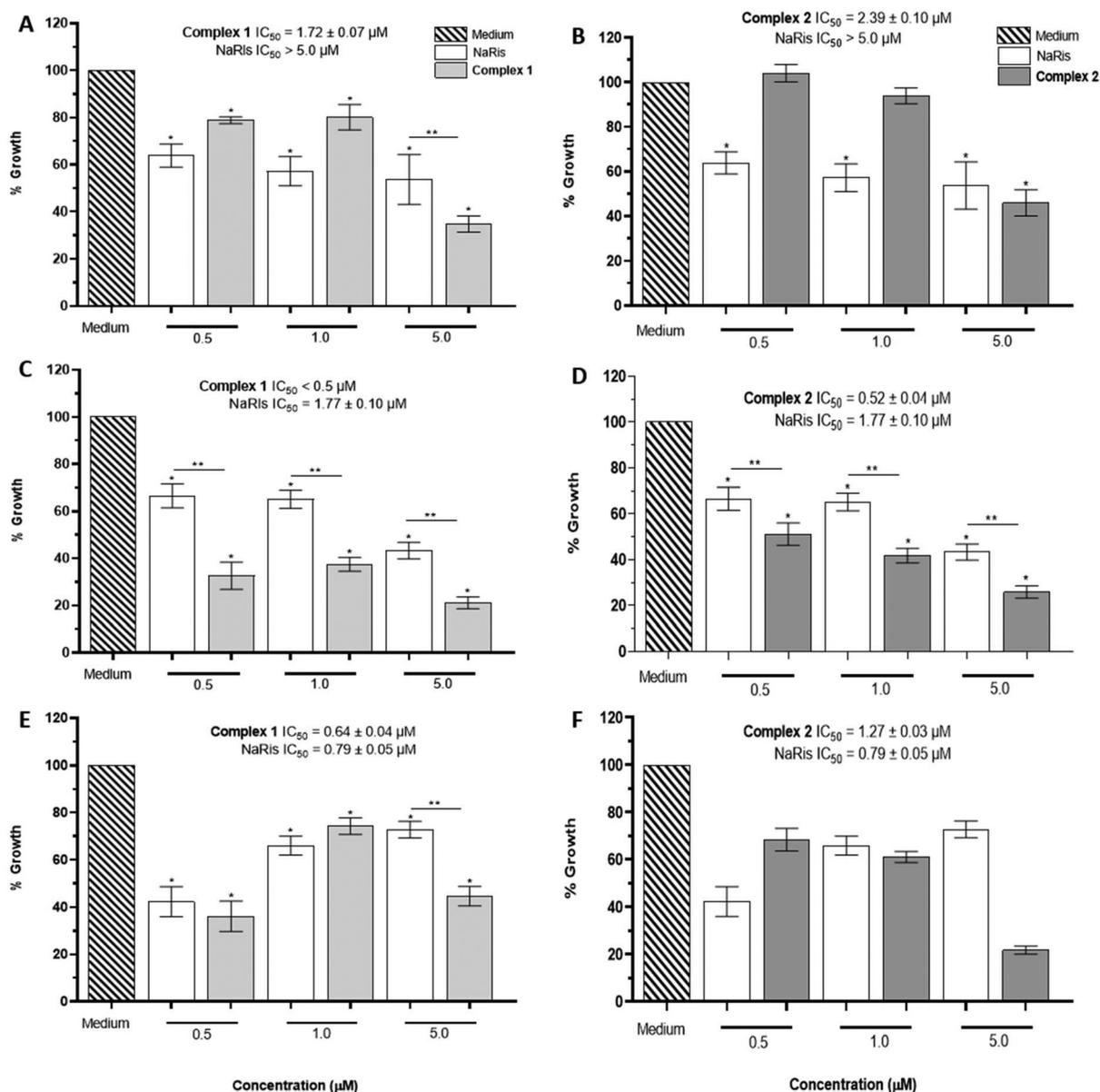
When we carried out the analysis of the interactions between enzyme and complex 1, we found that the amino acids LYS 51 (K51), LYS 207 (K207), GLN 247 (Q247), LYS 264 (K264) and LYS 362 (K362) are stabilizing of the binding in the complex 1-protein (Fig. 7A and B) with an estimated energy of  $\Delta G = -8.3 \text{ kcal mol}^{-1}$ .

Finally, we find for complex 2 that the interaction with amino acid residue LYS 207 (K207), ASP 254 (D254), LYS 264 (K264), VAL 265 (V265) are stabilizing of the binding between the enzyme and complex 2 (Fig. 8A and B) and with calculated energy of  $\Delta G = -8.5 \text{ kcal mol}^{-1}$ , which is slightly more negative than the energy found with complex 1.

Unlike NaRis, complexes 1 and 2 present interactions with the homoallylic region of the catalytic site (R51, Y49 interaction) conferring greater stability.

It is well-known that the FPPS enzyme catalyzes two consecutive condensation reactions, one of which takes place on a DMAPP allyl substrate and the other on the IPP homoallylic substrate, the end product of which is FPP.





**Fig. 5** Effect of complexes 1 and 2 on the growth of *L. mexicana* M379 promastigotes. Parasite culture ( $4 \times 10^5$  parasites in 200  $\mu\text{L}$ ) were incubated with 0.5, 1.0 and 5.0  $\mu\text{M}$  of NaRis, complex 1 and complex 2. Medium M199 was used as control. Growth was evaluated at 24 h (A and B), 48 h (C and D) and 72 h (E and F). The number of parasites after treatment was established by counting in a Neubauer chamber, using a Microstar IV microscope (Reichert, USA). The results are presented as the average percentage  $\pm$  the standard deviation of growth, from three independent experiments by duplicate. Ordinary one-way ANOVA was used for statistical analysis. The asterisk (\*) represents the statistically significant differences between the treatments compared to the control untreated parasite (medium) ( $p < 0.05$ ). (\*\*) asterisks represent the statistically significant differences between the treatments with NaRis with respect to treatments with complex 1 or complex 2 ( $p < 0.0001$ ).

The inhibition of this condensation involves the blocking of the synthesis of FPP, which is an interesting therapeutic target, and it has also been shown that several compounds derived from the phosphonate group have activity against several trypanosomatid organisms,<sup>47,48,77</sup> including the effect of the study carried out by Bouzahzah in 2005, where they showed that NaRis significantly increases the survival of mice that were infected with *T. cruzi*.<sup>78</sup>

Inhibition of these allylic and homoallylic sites are responsible for the inhibition of FPPS activity. According to our studies, we observed that comparing risedronate with compound 1, the latter interacts with the homoallylic region of the enzyme, which could be interpreted as a better inhibitor of FPPS activity, we also analyzed the favorable values of entropy, as previously reported, these values are very similar to those found by Aripirala.<sup>75</sup>



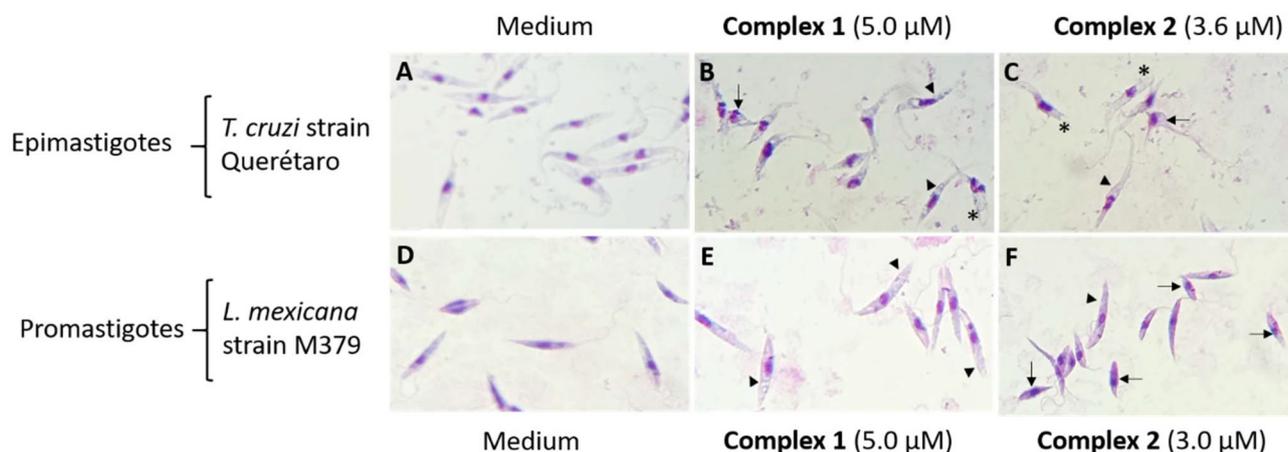
**Table 3** Cytotoxicity and antiparasitic activity of NaRis, 1 and 2

Compound	CC <sub>50</sub> (μM), (VERO)	IC <sub>50</sub> (μM), <i>T. cruzi</i> Qro	IC <sub>50</sub> (μM), <i>L. mexicana</i> M379
NaRis	0.61 ± 0.06	>7.6	>7.0
1	1.45 ± 0.04	5.27 ± 0.12	5.31 ± 0.03
2	0.67 ± 0.03	ND	3.97 ± 0.18

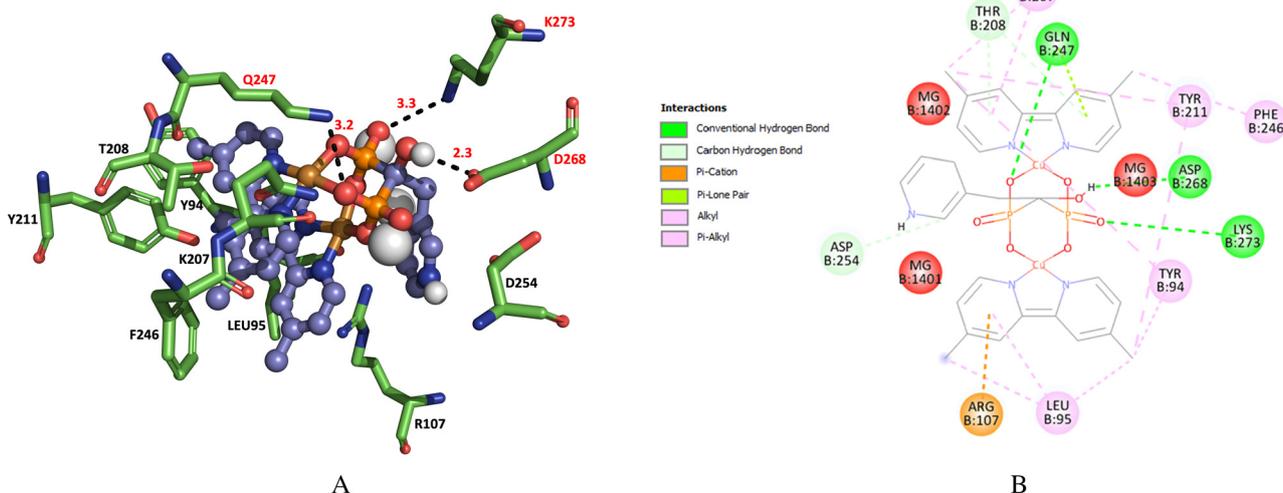
CC<sub>50</sub> cytotoxic concentration is the concentration that causes 50% of cell death IC<sub>50</sub> is the concentration that inhibits 50% metabolic activity. The values represent the average of 2 experiments ± standard deviation, evaluated by the MTT method after 48 h of incubation with the compounds. ND nor done.

These study reports that drug NaRis and complex 1 have interactions with all three Mg(II) atoms in their phosphate groups, while complex 2 interacts with only one Mg(II).

We also report the amino acids that are key to the interactions between each of the tested compounds and the TcFPPS enzyme, thus providing new knowledge about the interaction of new phosphonate derivatives with their target. Aripirala also reported that IPP binds to TcFPPS through Arg51, Arg 108 and Arg360 residues, while in our study we found that compound 1 also binds through its interaction with Arg51.<sup>75</sup>

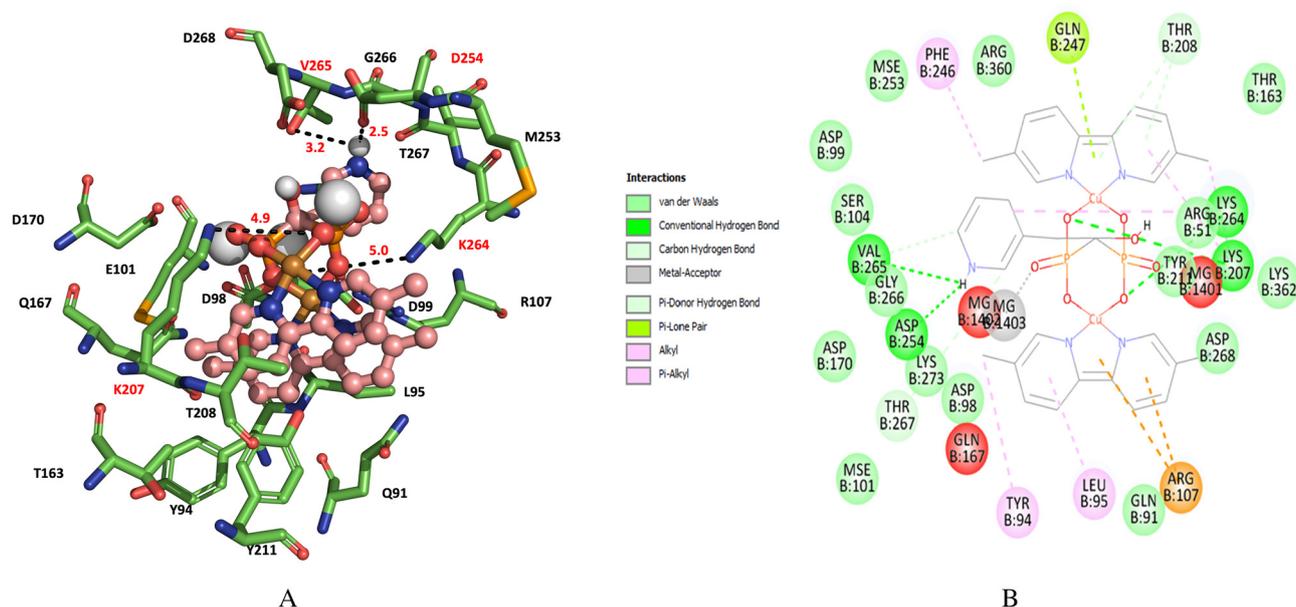


**Fig. 6** Morphological damage. Epimastigotes of *T. cruzi* Qro (B and C) and promastigotes of *L. mexicana* M379 (E and F) were incubated with complex 1 or complex 2 for 48 h at the indicated concentration; controls were incubated only with medium (A and D). Then they were fixed, stained with Giemsa, and observed in an optical microscopy at 40x. Morphological damage produced by the compounds (\*: damage to the cell membrane; arrowhead: increase in vacuolization; thin arrow: shortening of the parasite size).



**Fig. 7** (A) 3D and (B) 2D complex 1-protein interactions. (A) Black dotted lines correspond to H-bonds, distance of the bridges expressed in Å. The interacting residues with complex 1 are depicted as red. Images obtained using: PyMOL (TM) 2.5.4 from Schrodinger, LLC. (B) Electrostatic (van der Waals) and pi-alkyl interactions are observed. The interactions (attractive charges between the ligand and the Mg<sup>2+</sup> molecules) are key for the inhibition of the enzyme. Images obtained through Biovia Discovery studio visualize 2021 v 21.1.0.





**Fig. 8** (A) 3D and (B) 2D complex 2-protein interactions. (A) Black dotted line corresponds to H-bonds, distance of the bridges expressed in Å. The interacting residues with complex 2 are depicted as red. Images obtained using: PyMOL (TM) 2.5.4 from Schrodinger, LLC. (B) Electrostatic (van der Waals), pi-donor, pi-alkyl and carbon-hydrogen interactions are observed. The interactions (attractive charges between the ligand and the  $Mg^{2+}$  molecules) are key for the inhibition of the enzyme. Images obtained through Biovia Discovery studio visualize 2021 v 21.1.0.

## Conclusions

We have synthesized two novel water-soluble polynuclear  $Cu(II)$  compounds with the bioactive drug risedronate, a tetranuclear complex  $[Cu_4(4,4'-dmbp)_4(\mu_3-HRis)_2Cl_2]$ , **1** and a dinuclear complex  $[Cu_2(5,5'-dmbp)_2(\mu_2-HRis)(H_2O)Cl]$ , **2**.

These complexes were described structurally by single-crystal X-ray diffraction, characterized by several analytical tools (EPR, HRMS, UV-Vis, IR-ATR) and tested as *anti-Trypanosoma cruzi* and *anti-Leishmania mexicana* agents.

$Cu(II)$ -Ris complexes **1-2** may be readily prepared through the reaction of  $CuCl_2$ , a dimethyl-2,2'-bipyridine and disodium salt of risedronate in aqueous media.

Complex **1** possesses a tetranuclear  $Cu_4$  core containing two double-bridged bisphosphonate moieties from two different risedronate ligands in a coordination environment of  $\mu_3, \eta^4$ -bisphosphonate, while complex **2** involves a dinuclear  $Cu_2$  core built by a  $\mu_2, \eta^4$ -bisphosphonate. Such coordination modes of bisphosphonate moieties still are rare in literature.

Complexes **1-2** are hydrostable in the millimolar concentration range and present low cytotoxicity (<22% *in vitro* on the growth of cancer cell lines and on healthy COS-7 cells) similar to commercial drug NaRis.

The antiparasitic results demonstrated that  $Cu(II)$ -Ris complexes **1-2** have higher activity against epimastigote form of *T. cruzi* and the promastigote form of *L. mexicana* compared to NaRis in the low micromolar range, furthermore, these  $Cu(II)$ -compounds presented moderated selectivity index using VERO cells as mammalian cell model.

Importantly these complexes affected morphological damage that affects the viability of the parasites. The use of bioinformatics tools such as molecular docking provides a basis for the search for new trypanocidal agents, since these models provide information about the biological activity of new  $Cu(II)$ -Ris complexes.

Overall, these results further highlight the usefulness of water-soluble polynuclear  $Cu(II)$ -bipyridine complexes bearing the ligand risedronate as promising candidates for further anti-*T. cruzi* and anti-*L. mexicana* drug development. Studies of the effect of these compounds in infection *in vitro* and *in vivo* should be done in the future to have more information on these promising novel polynuclear  $Cu(II)$ -Ris compounds.

## Experimental section

### Materials and methods

General conditions, chemical reagents and equipment are described in the ESI.†

### Chemical synthesis of $Cu(II)$ -Ris complexes **1-2**

**Synthesis of 1,  $[Cu_4(4,4'-dmbp)_4(\mu_3-HRis)_2Cl_2]$ .**  $CuCl_2 \cdot 2H_2O$  (138 mg, 0.80 mmol) and 4,4'-dmbp (149 mg, 0.80 mol) were dissolved in  $CH_3OH$  (25 mL) and the mixture was stirred for 1 h at r.t. Subsequently, the solvent was removed under reduced pressure to give green crystals corresponding to the reported dinuclear complex  $[Cu_2(4,4'-dmbp)_2Cl_4] \cdot H_2O$ .<sup>79</sup> Then,  $[Cu_2(4,4'-dmbp)_2Cl_4] \cdot H_2O$  (26 mg, 0.04 mmol) was dissolved in



H<sub>2</sub>O (25 mL) and an aqueous solution (5 mL) of dianion Na<sub>2</sub>Ris (14 mg, 0.04 mmol) was slowly added at r.t. The reaction mixture was kept under stirring for 2 h and filtered. Prismatic aquamarine blue single crystals were obtained directly from the solution by slow evaporation after 1 week. Yield: 89% (27.6 mg) based on metal.

For elemental analysis, the crystalline sample was dried *in vacuo* at r.t for 24 h. Found: C, 43.56; H, 4.67; N, 8.14%. Calc. for [Cu<sub>4</sub>C<sub>62</sub>H<sub>64</sub>Cl<sub>2</sub>N<sub>10</sub>O<sub>14</sub>P<sub>4</sub>].4(H<sub>2</sub>O): C, 43.95; H, 4.28; N, 8.27%. IR-ATR (cm<sup>-1</sup>): 3372m ν(C-OH), 3056w ν(C<sub>aromatic</sub>-H), 1615s ν(C=C, C=N), 1222w ν<sub>as</sub>(PO<sub>2</sub><sup>-</sup>), 1131m ν<sub>s</sub>(PO<sub>2</sub><sup>-</sup>), 1023s ρ(C-H). m.p.: 215 °C. ESI(+)-HRMS (*m/z*): calculated for [Cu<sub>2</sub>C<sub>31</sub>H<sub>32</sub>N<sub>5</sub>O<sub>7</sub>P<sub>2</sub>]<sup>+</sup> corresponding to monocationic species [Cu<sub>2</sub>(4,4'-dmbp)<sub>2</sub>(HRis)]<sup>+</sup>, 774.036891. Found: 774.037583. UV-Vis: λ<sub>max</sub> (nm) in H<sub>2</sub>O: 646 (ε = 175 M<sup>-1</sup> cm<sup>-1</sup>). EPR (H<sub>2</sub>O, 77 K): *g*<sub>⊥</sub> = 2.0946 and *g*<sub>∥</sub> = 2.2400.

**Synthesis of 2, [Cu<sub>2</sub>(5,5'-dmbp)<sub>2</sub>(μ<sub>2</sub>-HRis)(H<sub>2</sub>O)Cl].** This compound was prepared following the same procedure as that for **1**, from 5,5'-dmbp instead 4,4'-dmbp. In this case, blue single crystals were obtained by slow evaporation from a solution of CH<sub>3</sub>OH/CH<sub>3</sub>CN (9/1, v/v) solution after 8 days. Yield: 82% (26.5 mg) based on metal.

For elemental analysis, the crystalline sample was dried *in vacuo* at r.t for 24 h. Found: C, 44.91; H, 4.13; N, 8.45%. Calc. for [C<sub>31</sub>H<sub>34</sub>ClCu<sub>2</sub>N<sub>5</sub>O<sub>8</sub>P<sub>2</sub>]: C, 44.78; H, 4.21; N, 8.40%. IR-ATR (cm<sup>-1</sup>): 3375m ν(C-OH), 3045w ν(C<sub>aromatic</sub>-H), 1476s ν(C=C, C=N), 1230w ν<sub>as</sub>(PO<sub>2</sub><sup>-</sup>), 1137m ν<sub>s</sub>(PO<sub>2</sub><sup>-</sup>), 1045s ρ(C-H). m.p. = 206 °C.

ESI(+)-HRMS (*m/z*): calculated for [C<sub>31</sub>H<sub>32</sub>Cu<sub>2</sub>N<sub>5</sub>O<sub>7</sub>P<sub>2</sub>]<sup>+</sup> corresponding to monocationic species [Cu<sub>2</sub>(5,5'-dmbp)<sub>2</sub>(HRis)]<sup>+</sup>, 774.036891. Found: 774.036804. UV-Vis: λ<sub>max</sub> (nm) in H<sub>2</sub>O: 643 (ε = 140 M<sup>-1</sup> cm<sup>-1</sup>). EPR (H<sub>2</sub>O, 77 K): *g*<sub>⊥</sub> = 2.0915 and *g*<sub>∥</sub> = 2.2325.

**Crystallographic investigations.** The relevant details of crystals, data collection and structure refinement of **1–2** can be found in Table S1.† These single-crystals were collected on a Bruker APEX II CCD diffractometer at 100 K, using Cu-K<sub>α</sub> radiation (*k* = 0.71073 Å) from an Incoatec ImuS source and Helios optic monochromator. Suitable single crystals were coated with hydrocarbon oil, picked up with a nylon loop, and mounted in the cold N<sub>2</sub> stream of the diffractometer. The structures were solved by direct methods<sup>80</sup> and refined by full-matrix least-squares on *F*<sup>2</sup> using the shelXle GUI.<sup>81,82</sup> The hydrogen atoms of the C–H and O–H bonds were placed in idealized positions, it was not possible to find the hydrogen atoms from O–H moiety in the map of residual density, and their position was refined with *U*<sub>iso</sub> = *aU*<sub>eq</sub>, where *a* is 1.5 for –CH<sub>3</sub> and –OH moieties and 1.2 for others.

In both cases, the highly disordered water molecules were modeled using the SQUEEZE tool implemented in PLATON.<sup>83</sup> The disorder moieties in complexes **1** and **2** were modeled using RIGU, SIMU, SAME and EADP instructions described in SHELXL.<sup>80</sup>

In complex **1**, in the axial position of Cu1 and Cu4 presented occupational disorder between Cl atoms and water molecules, for the Cu1 atom, the occupational ratio is 27/73

while for the Cu4 atom it is 40/60 between the Cl atoms and the water molecules respectively.

Because the two pyridinium fragments are protonated, it is necessary that the occupation of the Cl<sup>-</sup> ions is equal to 2, for this reason, the occupation of the Cl atoms is modeled in partial occupation of 73% for Cl2 and 60% for Cl4. However, the exact positions of the Cl<sup>-</sup> anions cannot be determined with certainty due to the possible positional disorder between Cl<sup>-</sup>/H<sub>2</sub>O of the highly disordered solvent that was modeled with the PLATON SQUEEZE tool. One of the pyridine moieties presents a positional disorder that was modeled in 2 positions in ratio 50/50.

In **2**, the axial position in the square-based pyramid geometry of the Cu(II) atom labeled as Cu2, presents occupational disorder in a 50/50 relationship with a Cl<sup>-</sup> atom and a water molecule, the charge of the Cl<sup>-</sup> atom with 50% occupation is balanced by a hydrogen atom with 50% occupation that protonates one of the oxygen atoms of the phosphate group. For the case of the occluded solvent molecules in the crystal of compound **2**, only two CH<sub>3</sub>CN molecules with occupancy of 71 and 52% respectively, as well as three water molecules with partial occupations of 33, 24 and 13% respectively, could be partially modeled. The molecular graphics were prepared using Olex2.<sup>84</sup> Crystallographic data for the two crystal structures have been deposited with the Cambridge Crystallographic Data Centre, no. CCDC 2329846 and 2396933.† X-ray crystallographic data in CIF format are available in ESI.†

**Cytotoxic assay.** The cells were removed from the tissue culture flasks by treatment with trypsin and diluted with fresh media. Of these cell suspensions, 100 μL per well containing 5000–10 000 cell per mL, were seeded in 96 well micro-titer plates (Costar) by triplicates and incubated at 37 °C for 24 h in a 5% CO<sub>2</sub> atmosphere to allow for cell attachment. After incubation, 100 μL of a solution of the compound obtained by diluting the stocks were added to each well. After 48 h, adherent cell culture was fixed *in situ* by the addition of 50 μL of cold 50% aqueous trichloroacetic acid (TCA), and incubated for 60 min at 4 °C. The supernatant was discarded, and the plates were washed with water and air-dried. Cultures fixed with TCA were stained by the addition of 0.4% SRB. Free SRB solution was removed by washing with 1% aqueous acetic acid. Protein bounded dye was extracted with 10 mM of non-buffered Tris base and the optical densities (515 nm) were measured on Microplate Reader Synergy (Bio-Tex Instruments).

**Culture of trypanosomatids *in vitro*.** *T. cruzi* epimastigotes of the Mexican Querétaro strain (TBAR/0000/MX/Querétaro) (*T. cruzi* Qro strain) were maintained in LIT medium (Becton Dickinson, USA, Cat. 226920) with 10% fetal bovine serum (SFB) (Gibco, USA, Cat. 15575309) and 25 μg mL<sup>-1</sup> hemin (Sigma, USA, Cat. H9039), at 28 °C as previously described.<sup>25</sup> The assay used parasites in the logarithmic growth phase (5 days with 40–60 × 10<sup>6</sup> parasites per mL). Promastigotes (infective stage) of *L. mexicana* M379 strain were maintained in medium 199 (M199) (Invitrogen, USA, Cat. 31100035) with 10% SFB and reseeded every third day for maintenance. Parasites in the log phase of growth (2 days of culture, 15–30 × 10<sup>6</sup> parasites per mL) were used for the tests.



**Evaluation of complexes 1 and 2 effects on *T. cruzi* and *L. mexicana* growth.** To evaluate the effect of each complex on the growth of *T. cruzi* and *L. mexicana*, the parasite stock was adjusted to  $2 \times 10^6$  parasites per mL, and 200  $\mu\text{L}$  of this culture was seeded in 96-well plates. NaRis or complex 1/complex 2 were added in concentrations of 0.5, 1.0, and 5.0  $\mu\text{M}$  and incubated at 28 °C for 24, 48, and 72 h. After these times, the number of parasites in each condition was counted using a Neubauer chamber and a Microstar IV microscope (Reichert, USA). Each condition was evaluated in duplicate in three independent experiments. The median inhibitory concentration (IC<sub>50</sub>) was calculated using the formula previously described.<sup>85</sup>

**Evaluation of morphological changes.** To observe the changes in the parasite morphology after the treatments, permanent microscopic preparations of treated and untreated parasites were made. Briefly,  $20 \times 10^3$  (5  $\mu\text{L}$ ) of *T. cruzi* epimastigotes or *L. mexicana* promastigotes were deposited in a perforated slide (Electron Microscopy Sciences, catalog 63429-04), air-dried for 20 min at room temperature, dehydrated in methanol for 5 min and stained with Giemsa (Sigma catalog 51811-82-6) for 15 min. The slides were washed three times with PBS and double distilled water, and finally, air dried and mounted in organo/limonene mounting resin (Santa Cruz Biotechnology, catalog Sc-45087) with a coverslip. Slides were observed in a Nikon Optiphot 2 light microscope coupled to a Nikon Coolpix 4300 digital camera. Multiple images were acquired, and at least 100 cells were counted in each independent experiment.

**Evaluation of the reductase metabolic activity by MTT assay.** Briefly,  $2 \times 10^6$  parasites of *L. mexicana* M379 and *T. cruzi* Querétaro were placed in 100  $\mu\text{L}$  of M199 and LIT medium respectively, at concentrations of complex 1 (1.2, 2.5, 5.0, 7.0, 9.0  $\mu\text{M}$ ) and complex 2 (1.5, 3.0, 6.0, 9.0, 12.0  $\mu\text{M}$ ), and incubated for 48 hours at 28 °C. After this time, they were centrifuged at 2500g for 10 min. Then, they were washed with 500  $\mu\text{L}$  sterile PBS and centrifuged at 2500g for 10 min. The pellets were resuspended in 24  $\mu\text{L}$  of non-complete LIT or medium M199 (without hemin and FBS) containing tetrazolium dye (MTT 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (0.5 mg mL<sup>-1</sup>)) and incubated at 28 °C for 4 h in the dark. The parasites were recovered by centrifugation. The formazan salt was dissolved in 40  $\mu\text{L}$  100% DMSO and stirred for 1 min at room temperature. Then, 20  $\mu\text{L}$  of each sample were placed in a 96-well round bottom plate and absorbance at 595 nm was determined with a 655 nm reference in a microplate reader (550, Bio-Rad).<sup>86</sup>

Samples were tested in duplicate in two independent assays, and the percentage of reductase activity was compared to total activity in the non-treated control group.

## Data availability

Crystallographic data for compounds 1 and 2 have been deposited at the Cambridge Crystallographic Data Centre under CCDC 2329846 (complex 1) and 2396933 (complex 2).†

## Conflicts of interest

There are no conflicts to declare.

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