Copper(I) iodide complexes containing new aliphatic aminophosphine ligands and diimines—luminescent properties and antibacterial activity†

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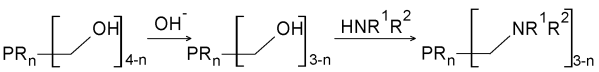
The new, water soluble, aminomethylphosphines were synthesized from $P(CH_2OH)_3$ and alkylpiperazines: $P(CH_2N(CH_2CH_2)_2NCH_3)_3$ (**1**) and $P(CH_2N(CH_2CH_2)_2NCH_2CH_3)_3$ (**2**). Described already in literature $P(CH_2N(CH_2CH_2)_2O)_3$ (**3**) were also obtained. The spectroscopic ^1H, ^{31}P and ^{13}C NMR analyses and crystallographic studies of **1**, **2** and **3** demonstrate that all these compounds have similar structures and spectroscopic properties, which almost do not depend on aliphatic rings in the molecules. Heteroleptic copper(I) iodide complexes with phosphines mentioned above and 2,2′-bipyridine (bpy): [CuI(bpy)$P(CH_2N(CH_2CH_2)_2NCH_3)_3$] (**1B**), [CuI(bpy)$P(CH_2N(CH_2CH_2)_2NCH_2CH_3)_3$] (**2B**), [CuI(bpy)$P(CH_2N(CH_2CH_2)_2O)_3$] (**3B**) or 1,10-phenanthroline (phen): [CuI(phen)$P(CH_2N(CH_2CH_2)_2NCH_3)_3$] (**1P**), [CuI(phen)$P(CH_2N(CH_2CH_2)NCH_2CH_3)_3$] (**2P**), [CuI(phen)$P(CH_2N(CH_2CH_2)_2O)_3$] (**3P**) were also synthesized. All complexes were characterized by ^1H, ^{31}P and ^{13}C NMR spectroscopy also. Molecular structures of **1P**·$PhCH_3$ and **3P**·$0.5Cu_2I_2(phen)_2$ were determined from single crystal X-ray diffraction studies. Upon excitation at 470 nm, all complexes in the solid state exhibit red photoluminescence due to charge transfer transition. The luminescence of phen complexes is higher than the luminescence of bpy ones. The presented phosphines and copper(I) complexes were screened for their *in vitro* antibacterial and antifungal activity against *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus* strains and *Candida albicans*. All the copper complexes exhibit significant antibacterial activity against *Staphylococcus aureus* strains. The activity of 1,10-phenanthroline complexes is higher than 2,2′-bipyridine complexes.

Introduction

Reactions of hydroxymethylphosphines of general formula $R_nP(CH_2OH)_{3-n}$ with amines or amino acids (Scheme 1) result in a variety of new aminomethylphosphines, which can find multiple applications in chemistry, biochemistry and biomedical sciences.

The synthesis of aliphatic aminomethylphosphines from the tetrakis(hydroxymethyl)phosphonium cation and dialkylamines was first described by Coates and Hoye[1] in 1960. Since that time, a number of aminomethylphosphines has been prepared.[2–17]

There are some known aminomethylphosphines with aromatic substituents.[7,8] A few examples of the highly water-soluble phosphines prepared from the aliphatic secondary amines are also known,[2] which exhibit electronic properties similar to the properties of the electron-rich trialkylphosphines. Tris(aminomethyl)phosphines prepared from amino acids[3–6] are also of general interest because of the potential conjugation of the amino acid derivatives and peptides with hydroxymethylphosphines.



Scheme 1 Formation of aminomethylphosphines (n = 0, 1, 2).

The high diversity of steric and electronic properties of aminomethylphosphines encouraged us to study this class of compounds. We chose the derivatives of piperazine because this compound is a common spacer in a large number of drugs and other biologically important compounds. We prepared two new phosphines: $P(CH_2N(CH_2CH_2)_2NCH_3)_3$ (**1**) and $P(CH_2N(CH_2CH_2)_2NCH_2CH_3)_3$ (**2**), and studied their coordination abilities. We also obtained a morpholine derivative: $P(CH_2N(CH_2CH_2)_2O)_3$ (**3**), which was already mentioned in literature,[1] for comparison purposes.

In this paper, we also describe the syntheses and properties of a series of copper(I) iodide complexes with **1**, **2** or **3** phosphines and 2,2′-bipyridine (bpy) or 1,10-phenanthroline (phen) ligands.

The choice of copper(I) cation was based on the following considerations. First, the copper(I) complexes with phosphines and 1,10-phenanthroline and its derivatives were extensively studied for their variable photophysical properties,[18–28] because of the strong dependence of the luminescence of copper(I) complexes on the diimine and phosphine ligands. Second, a

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number of copper(I) complexes with aromatic tertiary phosphines and diphosphines[29–37] were investigated for their tumoricidal properties. It was postulated that the biological activity of copper(I) with bidentate tertiary phosphines was mainly due to the action of the ligand.[29,30] It was also proved that the use of the water soluble phosphines is purposeful because the more hydrophilic and labile complexes of tris(hydroxymethyl)-phosphine with copper(I) were examined for their cytotoxic properties against a panel of human tumor cell lines, and found to be more active than complexes with diphosphines.[30,31]

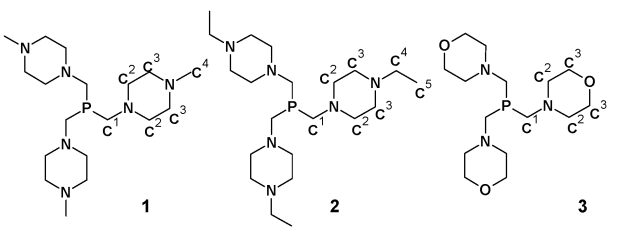
Results and discussion

Synthesis and characterization of phosphine ligands

We obtained three aliphatic aminomethylphosphines: **1**, **2** and **3** (Scheme 2) as the results of the reactions of $P(CH_2OH)_3$, obtained *in situ* from $P(CH_2OH)_4Cl$ after addition of a base (*i.e.* KOH or NEt_3; both bases give equal results) with *N*-methylpiperazine, *N*-ethylpiperazine or morpholine in water.

All the phosphines are well soluble in most common solvents: *i.e.* MeOH, EtOH, acetone, DMF, CH_3CN, CH_2Cl_2 and $CHCl_3$, and insoluble in hydrocarbons (*n*-hexane, cyclohexane). In addition, the phosphines are also well soluble in water. The solubility of compounds **1**, **2** and **3** in water are equal to 0.17, 0.09 and 0.16 g cm^{-3}, respectively. The ligands and their water or $CHCl_3$ solutions are air-stable.

NMR spectroscopy of phosphines. The $^{31}P\{^1H\}$, $^{13}C\{^1H\}$ and ^1H NMR spectra indicate undoubtedly very similar properties of phosphines **1**, **2** and **3** (see Experimental section). In the $^{31}P\{^1H\}$ NMR spectra, the phosphorus atom signal moved strongly to higher fields: $\delta(P) = -60.87$, -61.12 and -62.77 ppm for **1**, **2** and **3**, respectively. On the other hand, the three signals of the C^1, C^2 and C^3 carbon atoms (Scheme 2 presents the numbering scheme) in $^{13}C\{^1H\}$ NMR spectra clearly indicate that all three substituents are equivalent, and the piperazine or morpholine rings are freely rotating in solution. The spectral parameters of the C^1 atoms are very similar—their chemical shifts are about 59 ppm, and $^1J(C–P)$ coupling constants are about 4 Hz. The same is true for C^2 atoms: chemical shifts are 55–56 ppm and coupling constants $^3J(C–P)$ are 8 Hz—surprisingly larger than the $^1J(C–P)$ coupling constants. The signals of the C^3 atoms are singlets with more diverse chemical shifts because of the presence of the different substituents in the aliphatic rings. In the ^1H NMR spectra, H^1 protons have similar chemical shifts (about 2.6 ppm) and the coupling constants to the phosphorus atom $^2J(H^1P) \approx 3$ Hz. The signals of H^2 and H^3 atoms are broad multiplets. This broadening of the H^2 and H^3 proton signals results from conformational changes of labile 6-membered aliphatic rings. Lowering of the temperature results in slowing of the conformational movement of the rings. Gradual changes are observed in a full range of temperatures: from 298 to 213 K. Temperatures of coalescence depend strongly on the nature of the ring and are: 263–273 K for **1**, 273–283 K for **2** and 233–243 K for **3**. At low temperatures, the signals of the axial and equatorial protons are distinguishable. On the basis of the chemical shifts and the coupling constants we were able to assign all signals: pseudotriplets to axial, and moved to lower fields doublets to equatorial protons.



Scheme 2 The molecules of **1**, **2** and **3** ligands with atomic numeration scheme.

Crystallographic structures of phosphines. We determined the crystal structures of **1**, **2** and **3** phosphines. These structures are the first described structures of tris(aminomethyl)phosphines derived from the secondary amines. There are only two examples of the structures of amino acid derivatives: $P(CH_2NH_2^+-CH(CH_3)COO^-)_3$[4] and $P(CH_2NH_2^+CH_2COOH)_3Cl_3$,[5] and two aminomethylphosphines with aromatic substituents: $P(CH_2NH–C_6H_3\text{-}3,5\text{-}(CF_3)_2)_3$[7] and $P(CH_2NH–C_6H_4\text{-}2\text{-}COOCH_3)_3$,[8] in the literature, although a number of structures of phosphine derivatives of general structure X = $P(CH_2NH\text{-}Ar)_3$ have been reported.[7–8,38] Bond lengths and angles are summarized in Table 1. Perspective views of the phosphine molecules are depicted in Fig. 1–3.

Phosphine ligands crystallize in 2 types of molecular symmetry: strongly distorted C_{2v} symmetry (**1** and **3**) and C_3 symmetry (**2**). Compound **2** crystallizes with crystallographically-imposed C_3 symmetry with the phosphorus atom atop on the three-fold axis. Molecular symmetry depends mostly on the space orientation of the alkylpiperazine or morpholine rings. The geometry around the phosphorus atoms in **1** and **2** are very similar (Table 1). The geometry of **3** slightly differs from the geometries of **1** and **2**: the P–C bond length is shortened by 0.01 Å and the C–P–C bond angle is enlarged by 1°.

The packing of **3** is supported by weak intermolecular C–H···O hydrogen bonds[39,40] (Table 2.) between the CH_2 groups from the morpholine ring and the ring oxygen atom (Scheme 2: $C^2–H^2\cdots O^2$ and $C^3–H^3\cdots O^2$).

Synthesis and characterization of copper(I) complexes

From the reactions of **1**, **2** or **3** with copper(I) iodide and 2,2′-bipyridine (bpy) or 1,10-phenanthroline (phen) in 1 : 1 : 1

Table 1 Selected geometries of **1**, **2** and **3**

	1	2	3
P1–C11	1.853(2)	1.856(2)	1.840(3)
P1–C21	1.861(2)		1.853(3)
P1–C31	1.852(2)		1.843(3)
N11–C11	1.468(2)	1.465(2)	1.463(3)
N21–C21	1.466(2)		1.462(3)
N21–C21	1.465(2)		1.458(3)
C11–P1–C21	97.81(7)	97.91(8)	99.5(1)
C11–P1–C31	93.83(6)		95.3(1)
C21–P1–C31	102.02(6)		101.7(1)
P1–C11–N11	112.41(9)	112.6(1)	111.8(2)
P1–C21–N21	115.34(9)		113.2(2)
P1–C31–N31	115.70(9)		113.6(2)

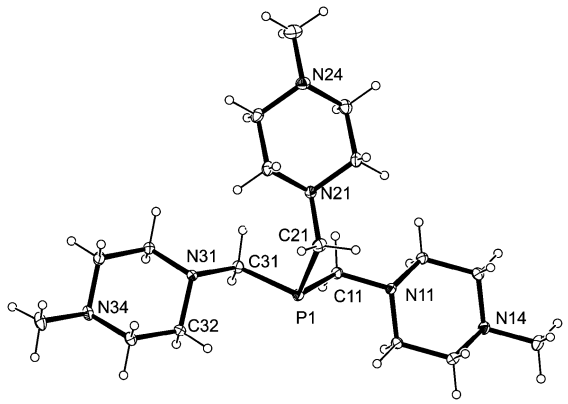


Fig. 1 ORTEP view (25% ellipsoids) of a molecule of **1**.

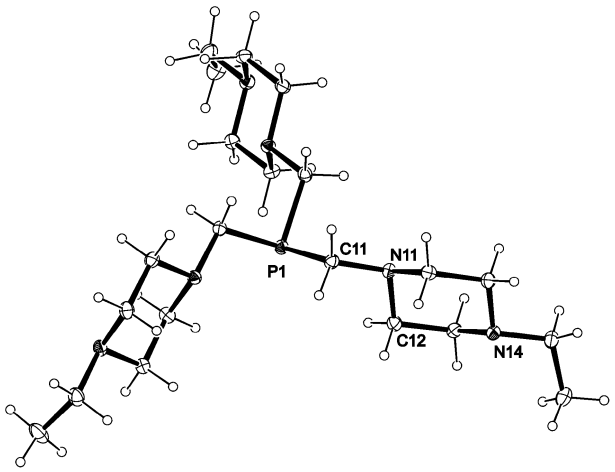


Fig. 2 ORTEP view (25% ellipsoids) of a molecule of **2**.

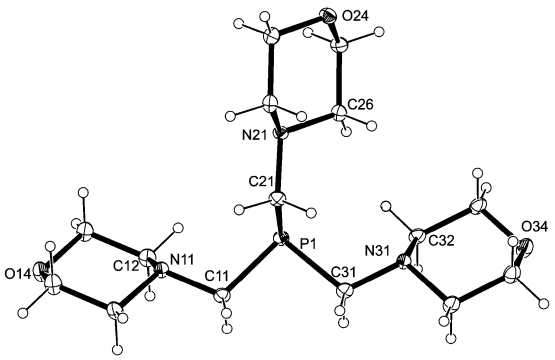


Fig. 3 ORTEP view (25% ellipsoids) of a molecule of **3**.

Table 2 Hydrogen bonds in **3**

DHA	D–H	H···A	D···A	<DHA
C(22)–H(22B)···O(14)i	0.99	2.47	3.431(3)	164
C(23)–H(23B)···O(34)ii	0.99	2.57	3.295(4)	130

Symmetry codes: [i] $2 - x + 1, -y + 1, -z$; [ii] $-x + 2, y - 1/2, -z + 1/2$.

molar ratio, we obtained a series of bright orange or yellow copper(I) complexes of general formula CuI(NN)P($CH_2N{=}R)_3$: [CuI(bpy)P($CH_2N(CH_2CH_2)_2NCH_3)_3$] (**1B**), [CuI(bpy)P-($CH_2N(CH_2CH_2)_2NCH_2CH_3)_3$] (**2B**), [CuI(bpy)P($CH_2N$-$(CH_2CH_2)_2O)_3$] (**3B**), [CuI(phen)P($CH_2N(CH_2CH_2)_2NCH_3)_3$] (**1P**), [CuI(phen)P($CH_2N(CH_2CH_2)_2NCH_2CH_3)_3$] (**2P**) and [CuI(phen)P($CH_2N(CH_2CH_2)_2O)_3$] (**3P**). The obtained complexes are soluble and air stable in most organic solvents. They are also well soluble and moderately stable in water solutions (for at least several hours with no observable diminishing of the intense orange color of the solution).

Crystallographic studies of copper(I) complexes. We have determined the crystal structure of the **1P**·$PhCH_3$ complex (Fig. 4 and 6). The elemental cell of **1P**·$PhCH_3$ complex contains two independent molecules (A and B) of the complex. We did not succeeded in obtaining crystals of **3P** or **2P** suitable for X-ray analysis; thus, we present the molecular structure of **3P**·$0.5Cu_2I_2(phen)_2$ in which **3P** complex co-crystallizes with the $Cu_2I_2(phen)_2$ molecule (lying about an inversion centre) in separate layers (Fig. 5 and 7). Forming this crystal indicates that the phosphine ligand is rather weakly bound to the copper cation and tends to dissociate.

The coordination polyhedrons around the Cu atoms in the molecules of **1P** and **3P** are the distorted tetrahedrons with the iodide anion, the phosphine molecule coordinating *via* the phosphorus atom, and phenanthroline acting as a bidentate ligand coordinating *via* two N atoms to the copper. Cu–I and Cu–P bond lengths (Table 3) in **1P**·$PhCH_3$ and **3P**·$0.5Cu_2I_2(phen)_2$ do not differ much from the Cu–I and Cu–P distances in analogous complexes: CuI(phen)PPh_3,[41] CuI(phen)$PPh_2CH_2CH_2PPh_2O$,[42] CuI(PPh_3)(DPPZ)·DMF[43] (DPPZ = dipyrido[3,2,-a:2′,3′-c]-phenazine) and CuI(PPh_3)(2,2′-bipy),[44] and depend on neither phosphine nor diimine ligand. Notable differences, however, are found in I–Cu–P bond angles: ave. 103.1(3)° for **1P**·$PhCH_3$, 107.06(5)° for **3P**·$0.5Cu_2I_2(phen)_2$, 112.70° for CuI(phen)PPh_3, 114.97° for CuI(PPh_3)(DPPZ)·DMF, 114.89° CuI(PPh_3)(2,2′-bipy) and 119.03° for CuI(phen)$PPh_2CH_2CH_2PPh_2O$.

The formation of copper(I) complexes causes notable changes in the geometry of the phosphine ligands. Coordination to the

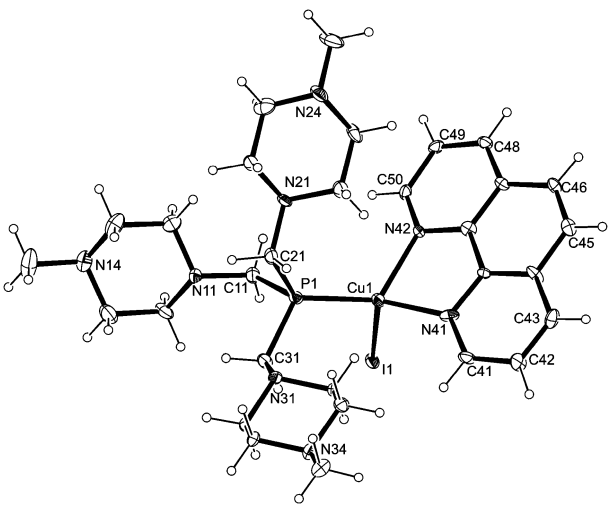


Fig. 4 ORTEP view (25% ellipsoids) of a B molecule of **1P**·$PhCH_3$.

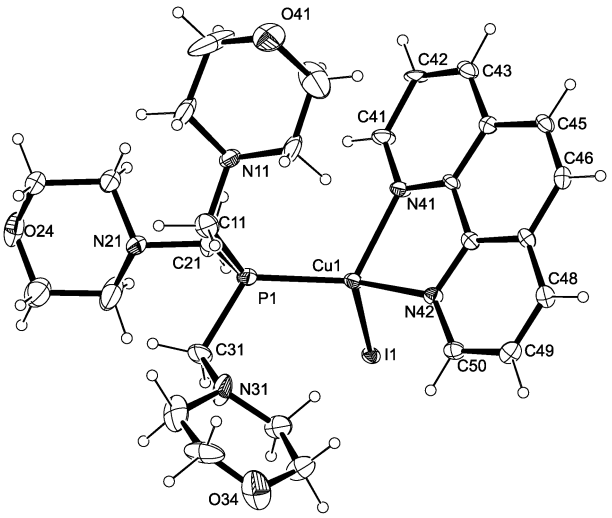


Fig. 5 Projection (ORTEP; 25% ellipsoids) of a molecule of **3P** in **3P**·0.5Cu_2I_2(1,10-phen)$_2$.

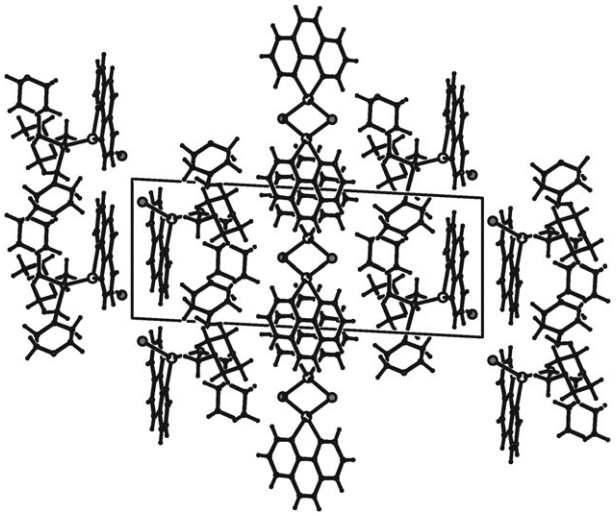


Fig. 7 PLATON XO view of crystal structure of **3P**·0.5Cu_2I_2(1,10-phen)$_2$.

copper(I) atom results in shortening of the C–P bonds from ave. 1.855(2) Å in **1** to ave. 1.84(2) Å in **1P**·$PhCH_3$, and from ave. 1.845(3) Å in **3** to ave. 1.837(6) Å in **3P**·0.5Cu_2I_2(phen)$_2$. These changes are accompanied by the increase of the of C–P–C bond angle values to from ave. 97.89(6)° in **1** to ave. 100.5(8)° in **1P**·$PhCH_3$, and from ave. 98.8(1)° in **3** to ave. 100.4(3)° in **3P**·0.5Cu_2I_2(phen)$_2$.

The 1,10-phenanthroline ligands of molecules A and B are packed in a parallel fashion in **1P**·$PhCH_3$ with partial overlapping, with centroid–centroid separation of 3.54 Å (Fig. 6). Molecules of **3P** are packed in a similar way to the packing of **1P** molecules in **1P**·$PhCH_3$.

NMR spectroscopy of copper(I) complexes. All obtained complexes were characterized by means of NMR spectroscopy. Coordination of the phosphine and phen or bpy molecules to the copper atom leads to large changes in the NMR spectra compared with free ligands.

In $^{31}P\{^1H\}$ NMR spectra signal of phosphorus is largely a broadened singlet moved to lower fields (from *ca.* −60 to *ca.* −30 ppm), both at 295 and 223 K temperatures. Coordination to the copper(I) atom strongly affects the phosphine H^1 protons and C^1 carbon atoms. The average chemical shift of H^1 is 2.60 ppm in phosphines (**1**, **2** and **3**) and 2.86 ppm in complexes. The signals of the H^1 protons are singlets despite no significant broadening of the signal. The signals of the phosphine C^1 carbon atoms are moved to higher fields from ave. 59.0 to ave. 55.5 ppm upon coordination. This shift is accompanied by a large increase of the $^1J(C^1–P)$ coupling constant: from ave. 4.2 Hz in free ligands to ave. 25.4 Hz in complexes. The signals of the ring carbon atoms are only slightly affected by coordination to the copper atom. The same is true for H^2 and H^3 protons. Surprisingly, H^3 protons of the phosphine rings are changed more than H^2 protons upon formation of the complexes.

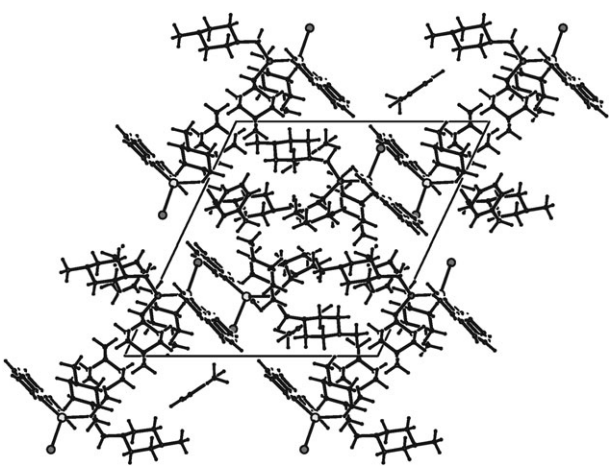


Fig. 6 PLATON XO view of crystal structure of **1P**·$PhCH_3$.

The signals of phen protons are moved to lower fields in all complexes. The largest average (for **1P**, **2P** and **3P**) difference in chemical shifts at room temperature is found for $H^{3,8}$ protons (0.26 ppm) and the smallest for $H^{5,6}$ protons (0.17 ppm). The signals of the protons of bpy are affected by the coordination to the copper atom even more. The signals of the $H^{4,4'}$and $H^{3,3'}$protons are moved to lower fields; $H^{5,5'}$ and $H^{6,6'}$ to higher fields. The average differences between chemical shifts in the complexes and free bpy are: 0.69, 0.34, −0.03 and −0.27 ppm for $H^{4,4'}$, $H^{3,3'}$, $H^{6,6'}$and $H^{5,5'}$protons, respectively.

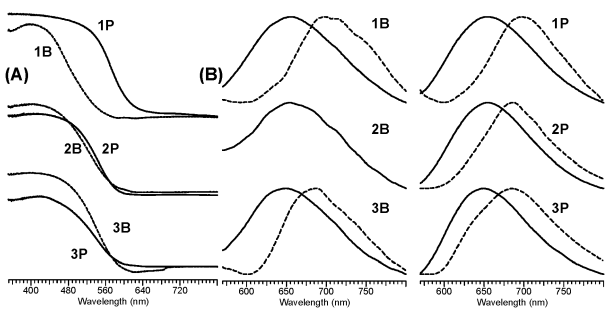
Solid state photophysical properties of copper(I) complexes

All complexes in the solid state exhibit photoluminescence. The electronic reflectance and normalized emission spectra of **1B–3P** solids are shown in Scheme 3, emission spectra parameters are summarized in Table 4. Reflectance spectra of powdered solids show an absorption band in the visible range of the spectra starting from *ca.* 600 nm with broad maxima between 400–500 nm from charge-transfer (CT) transitions, which correspond with the orange or yellow color of the complexes.

Complexes **1B–3P** emit in the red region with a broad emission band at about 650 nm at room temperature when excited by the CT energy (λ_{ex} = 470 nm). The emission band is

Table 3 Selected geometries of **1P**·$PhCH_3$ and **3P**·$0.5Cu_2I_2(1,10\text{-phen})_2$

	1P·$PhCH_3$ mol. A	**1P**·$PhCH_3$ mol. B	**3P**·$0.5Cu_2I_2(phen)_2$
Cu1–I1	2.615 (2)	2.619 (2)	2.631(1)
Cu1–N42	2.072(13)	2.085(11)	2.058(4)
Cu1–N41	2.092(12)	2.063(13)	2.101(4)
Cu1–P1	2.209 (4)	2.197 (4)	2.193(2)
P1–C11	1.839(19)	1.843(16)	1.835(6)
P1–C21	1.834(17)	1.816(17)	1.830(6)
P1–C31	1.867(16)	1.836(15)	1.846(6)
N11–C11	1.44(2)	1.472(19)	1.439(7)
N21–C21	1.43(2)	1.459(19)	1.470(7)
N31–C31	1.45(2)	1.432(19)	1.445(9)
N41–Cu1–N42	80.8(5)	81.3(5)	80.20(17)
I1–Cu1–N42	109.8(3)	107.9(3)	107.06(12)
I1–Cu1–N41	118.1(3)	108.4(4)	111.50(12)
I1–Cu1–P1	102.80(14)	103.52(14)	107.06(5)
N41–Cu1–P1	115.4(4)	131.9(4)	115.46(14)
N42–Cu1–P1	130.1(4)	121.6(3)	132.79(13)
C11–P1–Cu1	109.5(6)	108.3(5)	125.2(2)
C21–P1–Cu1	124.9(6)	126.1(5)	106.9(2)
C31–P1–Cu1	117.5(6)	117.0(6)	119.8(3)
C11–P1–C21	101.6(8)	100.2(8)	100.1(3)
C11–P1–C31	99.9(8)	101.5(7)	99.2(3)
C21–P1–C31	99.6(8)	100.0(7)	101.9(3)
P1–C11–N11	114.6(13)	114.8(11)	113.4(4)
P1–C21–N21	114.5(11)	111.5(11)	116.4(4)
P1–C31–N31	113.8(12)	113.9(11)	111.8(5)



Scheme 3 Reflectance spectra (A: **1B–3B**: ---; **1P–3P**: —) at room temperature and normalized luminescence spectra (B: 77 K: ---; 298 K: —) (λ_{ex} = 470 nm).

Table 4 Emission data (λ_{ex} = 470 nm)

Compound:	λ_{em} (298 K) nm	λ_{em} (77 K) nm
1B	655	697
2B	653	
3B	648	688
1P	653	698
2P	655	687
3P	650	685

strongly red-shifted compared to the emission band of pseudohalide copper complex [Cu(NCS)(phen)(PPh_3)] at λ_{em} = 490 nm (r.t.; CH_2Cl_2)[27] and comparative with the emission band at 620 nm (r.t.; solid state) of the copper(I) iodide complex with triphenylphosphine and dipyrido[3,2,-a:2′,3′-c]-phenazine [CuI(PPh_3)(DPPZ)]·DMF.[43] The luminescence of 2,2′-bipyridine complexes **1B**, **2B** and **3B** is very weak. Decrease of the temperature from 298 to 77 K results in a red shift of the λ_{em} for **1B** (42 nm) and **3B** (40 nm), while the luminescence of **2B** is fading. Phenanthroline complexes **1P**, **2P** and **3P** show more intense luminescence both at room and liquid nitrogen temperature with the red shift of λ_{em} of 45, 32 and 35 nm, respectively.

Antibacterial and antifungal activity

The studied phosphines and their copper(I) complexes were screened for their *in vitro* antibacterial activity against Gram-negative *Escherichia coli* (EC) and *Pseudomonas aeruginosa* (PA), as well as Gram-positive *Staphylococcus aureus* (SA) strains, and for *in vitro* antifungal activity against *Candida albicans* (CA). Briefly, to a series of tubes containing appropriate amounts of compounds, the microbial suspension and Antibiotic Broth were added. Complexes were prepared as the thin films on the walls of the tubes. The following concentrations of each compound were obtained: 2.56, 1.28, 0.64, 0.32, 0.16, 0.08 mg ml^{-1}. The minimal inhibitory concentrations (MICs) are given in Table 5.

The most active of the phosphines tested was **3**—its MIC values against *E. coli*, *P. aeruginosa* and *C. albicans* amounted to 1.28 mg ml^{-1}. *Staphylococcus aureus* was more susceptible; its growth was inhibited by a concentration of 0.64 mg ml^{-1}. Both remaining substances of the group tested showed no antimicrobial activity. The exception was phosphine **1** with a noticeable antifungal activity (MIC 0.64 mg ml^{-1}).

The copper complexes showed far stronger activity towards the microbial strains than phosphines. In comparison to bipyridine complexes, much higher activity of phenanthroline complexes was noticed.

Staphylococcus aureus was the most susceptible to all tested copper complexes, and its growth was inhibited by low concentrations of the substances. Also, it is worth mentioning that relatively equal effectiveness of derivatives/complexes within the group towards the staphylococcus strain was observed. On the contrary, *Pseudomonas aeruginosa* revealed high resistance rate against both groups of copper complexes examined. Only

Table 5 Antibacterial and antifungal activity against *Escherichia coli* (EC), *Pseudomonas aeruginosa* (PA), *Staphylococcus aureus* strains (SA), and *Candida albicans* (CA). MIC: c/mg ml^{-1}

	EC	PA	SA	CA
1	> 2.56	> 2.56	> 2.56	0.64
2	> 2.56	> 2.56	> 2.56	> 2.56
3	1.28	1.28	0.64	1.28
1B	2.56	2.56	0.32	1.28
2B	1.28	2.56	0.32	2.56
3B	0.64	2.56	0.32	2.56
1P	0.32	2.56	0.08	0.16
2P	0.32	1.28	0.08	0.16
3P	0.32	2.56	0.08	0.16

a high concentration (1.28 mg ml^{-1}) of **2P** was able to inhibit growth of the strain. Complexes **1P**, **2P** and **3P** were characterized by quite strong antifungal activity, while the other group had no such properties.

Experimental

All reactions were carried out under a dinitrogen atmosphere using standard Schlenk techniques. $P(CH_2OH)_4Cl$ (80% in H_2O, Fluka), 1-methylpiperazine and 1-ethylpiperazine (Aldrich) were used without further purification. Morpholine (POCh) was purified by distillation under N_2 prior to use. Water was distilled and degassed. NEt_3 was dried and distilled under dinitrogen atmosphere prior to use. All solvents were used without purification; only deaerated prior to use.

Spectroscopic methods

Mass spectra were recorded on a Bruker Daltonics micrOTOF-Q mass spectrometer equipped with electrospray ionization (ESI) source and operated in positive ion mode. Elemental analysis was performed with a Vario EL3 CHN analyzer. NMR spectra were recorded on a Bruker AMX 300 ($^{13}C\{^1H\}$, $^{31}P\{^1H\}$ and $^{77}Se\{^1H\}$) or Bruker AMX 500 (^1H NMR) spectrometers with traces of solvent as an internal reference for ^1H (acetone-d_6 δ = 2.04, $CDCl_3$ δ = 7.25 ppm) and 85% H_3PO_4 in H_2O as an external standard for ^{31}P. The splitting of proton resonances in the reported ^1H NMR spectra are defined as s = singlet, d = doublet, t = triplet and m = multiplet. UV-Vis reflectance spectra were recorded on Cary 5 spectrometer. Photoluminescence measurements were performed at room (298 K) and liquid nitrogen (77 K) temperatures using a SpectraPro 750 monochromator, equipped with Hamamatsu R928 photomultiplier and a 1200 L mm^{-1} grating blazed at 500 nm. A 450 W xenon arc lamp was used as an excitation source. It was coupled with 275 mm excitation monochromator which used a 1800 Lmm^{-1} grating blazed at 250 nm.

Syntheses

$P(CH_2N(CH_2CH_2)NCH_3)_3$ (1). To a solution of 7.331 g (38.8 mmol) of $P(CH_2OH)_4Cl$ in 35 ml of water placed on the ice bath, NEt_3 (15 ml) was added drop wise. After 15 min of stirring *N*-methylpiperazine (11.669 g; 116.5 mmol) was added in four portions. The mixture was stirred for 1 h at room temperature. The product was extracted three times with 20 ml of $CHCl_3$. Chloroform extract was washed with a small amount of water and then most of the solvent was removed at reduced pressure. The oily phosphine was dissolved in 5 ml of acetone and left overnight at −18 °C. Colorless crystals were filtered off and dried *in vacuo*. Yield 55%. MS (MeOH): 393.3 NaM^+ 100%; 409.3 $NaOM^+$ 20%; 327.2 $(M(CH_3)_2 + 2H)^+$ 10%; 795.6 1%. NMR (acetone-d_6): $^{31}P\{^1H\}$ (298 K): −60.87 ppm, ^1H (298 K): H^1: 2.58 d $^2J(H^1P)$ = 3.03, H^2: 2.50 s, H^3: 2.31 s, H^4: 2.15 s, $^{13}C\{^1H\}$ (298 K): C^1: 58.69 d $^1J(C^1P)$ = 3.5, C^2: 55.21 d $^3J(C^2P)$ = 7.9, C^3: 55.73 s, C^4: 46.25 s, ^1H (213 K): H^1: 2.52 d $^2J(H^1P)$ = 1.85, H^{2B}: 2.83 d $^2J(H^{2B}H^{2A})$ = 10.34, H^{2A}: 2.05 t $^{2,3}J(H^{2A}H^{2B}H^{3B})$ = 10.99, H^{3B}: 2.61 d $^2J(H^{3B}H^{3A})$ = 10.34, H^{3A}: 1.90 t $^{2,3}J(H^{3A}H^{3B}H^{2B})$ = 10.44, H^4: 2.10 s, $^{13}C\{^1H\}$ (213 K): C^1 58.60 d $^1J(C^1P)$ = 3.1, C^2: 55.07 d $^3J(C^2P)$ = 8.3, C^3: 55.56 s, C^4: 46.18 s. Anal. Calcd for $C_{18}H_{39}N_6P$: C, 58.35; H, 10.61; N, 22.68. Found: C, 58.20; H, 10.89; N, 22.52%.

$P(CH_2N(CH_2CH_2)_2NCH_2CH_3)_3$ (2). To a solution of 6.172 g (32.4 mmol) of $P(CH_2OH)_4Cl$ in 35 ml of water placed on the ice bath, KOH (7.6978 g; 1.3721 mmol) was added. (Using excess of NEt_3 in other experiments gave the same results.) Then, *N*-ethylpiperazine (11.089 g; 97.1 mmol) was slowly added. The mixture was stirred for 1 h at room temperature. The product was extracted three times with 20 ml of $CHCl_3$. The chloroform extract was washed with a small amount of water and then most of the solvent was removed at reduced pressure. The oily phosphine was dissolved in 5 ml of acetone, which was removed at reduced pressure. White solid was redissolved in 5 ml of DMF in 50 °C and then left overnight at −18 °C. Colorless crystals were filtered off and dried *in vacuo*. Yield 67%. MS (MeOH): 413.3 HM^+ 5%; 435.3 NaM^+ 100%; 437.2 1% 451.3 $NaOM^+$ 1%. NMR (acetone-d_6): $^{31}P\{^1H\}$ (298 K): −61.12 ppm, ^1H (298 K): H^1: 2.58 d $^2J(H^1P)$ = 2.88, H^2: 2.50 s, H^3: 2.36 s, H^4: 2.29 q $^3J(H^4H^5)$ = 7.17, H^5: 0.99 t $^3J(H^5H^4)$ = 7.20, $^{13}C\{^1H\}$ (298 K): C^1: 59.03 d $^1J(C^1P)$ = 4.70, C^2: 55.73 d $^3J(C^2P)$ = 7.97, C^3: 53.84 s, C^4: 52.88 s, C^5: 12.71 s, ^1H (213 K): H^1: 2.54 d $^2J(H^1P)$ = 2.24, H^{2B}: 2.86 d $^2J(H^{2B}H^{2A})$ = 10.55, H^{2A}: 2.06 t $^{2,3}J(H^{2A}H^{2B}H^{3B})$ = 10.77, H^{3B}: 2.75 d $^2J(H^{3B}H^{3A})$ = 10.40, H^{3A}: 1.89 t $^{2,3}J(H^{3A}H^{3B}H^{2B})$ = 10.48, H^4: 2.24 q $^3J(H^4H^5)$ = 7.03, H^5 0.96 t $^3J(H^5H^4)$ = 7.19, $^{13}C\{^1H\}$ (213 K): C^1: 58.63 d $^1J(C^1P)$ = 3.2, C^2: 55.18 d $^3J(C^2P)$ = 8.3, C^3: 53.43 s, C^4: 52.60 s, C^5: 12.65 s. Anal. Calcd for $C_{21}H_{45}N_6P$: C, 61.13; H, 10.99; N, 20.37. Found: C, 60.97; H, 10.84; N, 20.12%.

$P(CH_2N(CH_2CH_2)_2O)_3$ (3). To a solution of 6.085 g (31.9 mmol) of $P(CH_2OH)_4Cl$ in 50 ml of water placed on the ice bath, NEt_3 (12 ml) was added drop wise. After 15 min of stirring, morpholine (8.3452 g; 95.8 mmol) was added in four portions. The mixture was stirred for 1 h at room temperature. The product was extracted three times with 20 ml of $CHCl_3$. Chloroform extract was washed with a small amount of water and then the solvent was removed at reduced pressure. The oily phosphine was dissolved in 5 ml of acetone and left overnight at −18 °C. Colorless crystals were filtered off and dried *in vacuo*. Yield 52%. MS (acetone + H_2O): 370.2 $NaOM^+$ 100%, 400.2 28%, 332.2 HM^+ 19%. NMR (acetone-d_6): $^{31}P\{^1H\}$ (298 K): −62.77 ppm, ^1H (298 K): H^1: 2.64 d $^2J(H^1P)$ = 2.95, H^2: 2.49 m, H^3: 3.58 m, $^{13}C\{^1H\}$

(298 K): C^1: 59.3 d $^1J(C^1P)$ = 4.3, C^2: 56.11 d $^3J(C^2P)$ = 8.1, C^3: 67.57 s, ^1H (213 K): H^1: 2.58 d $^2J(H^1P)$ = 2.07, H^{2B}: 2.81 d $^2J(H^{2B}H^{2A})$ = 11.24, H^{2A}: 2.07 t $^{2,3}J(H^{2A}H^{2B}H^{3B})$ = 10.75, H^{3B}: 3.69 d $^2J(H^{3B}H^{3A})$ = 10.59, H^{3A}: 3.40 t $^{2,3}J(H^{3A}H^{3B}H^{2B})$ = 10.91, $^{13}C\{^1H\}$ (213 K): C^1 58.80 d $^1J(C^1P)$ = 2.3, C^2: 55.58 d $^3J(C^2P)$ = 8.5, C^3: 67.00 s. Anal. Calcd for $C_{15}H_{30}N_3O_3P$: C, 54.36; H, 9.12; N, 12.68. Found: C, 54.17; H, 9.23; N, 12.54%.

[CuI(bpy)P(CH$_2$N(CH$_2$CH$_2$)$_2$NCH$_3$)$_3$] (1B). A CH_2Cl_2–cyclohexane (1 : 1 V : V) solution (20 mL) containing **1** (0.3374 g; 0.91 mmol), CuI (0.1734 g; 0.91 mmol) and 2,2′-bpy (0.1422 g; 0.91 mmol) was stirred at room temperature for 2 h. The obtained red solution was evaporated to dryness. The obtained orange solid was washed twice with cyclohexane and dried under vacuum. Yield 87%. MS(acetone): (*m*/*z*) 638.6; 561.1; 433.2-[CuP(CH$_2$pipCH$_3$)$_3$]$^+$; 393.3; 371.3; 219.0; 184.0; 127.1; 113.1. NMR (acetone-d$_6$): $^{31}P\{^1H\}$ (298 K): −34 (s*) ^1H (298 K): $H^{3,3'}$ 8.97 (d, J = 4.54 Hz), $H^{6,6'}$ 8.45 (d, J = 8.24 Hz), $H^{4,4'}$ 8.05 (ddd, J = 7.81, 1.70 Hz), $H^{5,5'}$ 7.59 (ddd, J = 7.38, 5.11 Hz), $H^{1\text{-}P}$ 2.86 (s), $H^{2\text{-}P}$ 2.58 (s), $H^{3\text{-}P}$ 2.25 (s), $H^{4\text{-}P}$ 2.12 (s); $^{13}C\{^1H\}$ (298 K): $C^{3,3'}$ 150.70 (s), $C^{5,5'}$ 138.38 (s), $C^{4,4'}$ 125.85 (s), $C^{6,6'}$ 122.15 (s), $C^{2\text{-}P}$ 56.13 (s), $C^{3\text{-}P}$ 55.96 (s), $C^{1\text{-}P}$ 55.37 (d, *J* = 25 Hz), $C^{4\text{-}P}$ 46.24 (s). Anal. Calcd for $C_{28}H_{47}CuIN_8P$: C, 46.89; H, 6.61; N, 15.62. Found: C, 46.59; H, 6.62; N, 15.47%.

[CuI(bpy)P(CH$_2$N(CH$_2$CH$_2$)$_2$NCH$_2$CH$_3$)$_3$] (2B). A CH_2Cl_2–cyclohexane (1 : 1 V : V) solution (20 mL) containing **2** (0.3660 g; 0.64 mmol), CuI (0.1227 g; 0.64 mmol) and 2,2′-bpy (0.0858 g; 0.64 mmol) was stirred at room temperature. The obtained orange solution during that time changed its color to red. After 3 h, the solution was evaporated to dryness. The obtained orange solid was washed twice with cyclohexane and dried under vacuum. Yield 92%. MS (acetone):(*m*/*z*) 655.3-[Cu(bpy)-P(CH$_2$pipC$_2$H$_5$)$_3$]$^+$; 631.3; 603.2-[Cu P(CH$_2$pipC$_2$H$_5$)$_3$IH]$^+$; 475.3-[CuP(CH$_2$pipC$_2$H$_5$)$_3$]$^+$; 375.1-[Cu(bpy)$_2$]$^+$. NMR (acetone-d$_6$): $^{31}P\{^1H\}$ (298 K): -33 (s*) ^1H (298 K): $H^{3,3'}$ 9.03 (d, J = 4.54 Hz), $H^{6,6'}$ 8.45 (d, J = 7.95 Hz), $H^{4,4'}$ 8.05 (ddd, J = 7.81, 1.70 Hz), $H^{5,5'}$ 7.60 (ddd, J = 7.45, 5.04 Hz), $H^{1\text{-}P}$ 2.87 (s), $H^{2\text{-}P}$ 2.59 (s), $H^{3\text{-}P}$ 2.32 (s) $H^{4\text{-}P}$ 2.26 (q. J = 7.10), $H^{5\text{-}P}$ 0.97 (t, J = 7.24 Hz) $^{13}C\{^1H\}$ (298 K): $C^{1,1'}$ 152.85 (s), $C^{3,3'}$ 150.81 (s), $C^{5,5'}$ 138.46 (s), $C^{4,4'}$ 125.99 (s), $C^{6,6'}$ 122.31 (s), $C^{2\text{-}P}$ 56.28 (d, J = 4.33 Hz), $C^{1\text{-}P}$ 55.13 (d, J = 26.45 Hz), $C^{3\text{-}P}$ 53.62 (s), $C^{4\text{-}P}$ 52.72 (s), $C^{5\text{-}P}$ 12.51 (s). Anal. Calcd for $C_{31}H_{53}CuIN_8P$: C, 49.04; H, 7.04; N, 14.76. Found: C, 48.70; H, 6.99; N, 14.60%.

[CuI(bpy)P(CH$_2$N(CH$_2$CH$_2$)$_2$O)$_3$] (3B). A CH_2Cl_2–cyclohexane (1 : 1 V : V) solution (20 mL) containing **3** (0.4348 g; 1.3 mmol), CuI (0.2498 g; 1.3 mmol) and 2,2′-bpy (0.2049 g; 1.3 mmol) was stirred at room temperature. The obtained orange solution during that time changed its color to red. After 3 h, the solution was evaporated to dryness. The obtained orange solid was washed twice with cyclohexane and dried under vacuum. Yield 90%. MS (acetone): (*m*/*z*) 666.6; 638.6; 574.2- [CuNa(bpy)P(CH$_2$NC$_4$H$_8$O)$_3$]$^+$; 413.3; 381.3; 370.2; 353.3; 332.2. NMR (acetone-d$_6$): $^{31}P\{^1H\}$ (298 K): −35 (s*) ^1H (298 K): $H^{3,3'}$ 9.02 (d, J = 3.98 Hz), $H^{6,6'}$ 8.46 (d, J = 7.95 Hz), $H^{4,4'}$ 8.08 (td, J = 7.74, 1.56 Hz), $H^{5,5'}$ 7.64 (dd, J = 6.53, 5.11 Hz), $H^{3\text{-}P}$ 3.47 (m), $H^{1\text{-}P}$ 2.88 (s), $H^{2\text{-}P}$ 2.56 (m) $^{13}C\{^1H\}$ (298 K): $C^{1\text{-}P}$ 55.85 (d, J = 25.97 Hz) $C^{2\text{-}P}$ 56.59 (d, J = 5.77 Hz) $C^{3\text{-}P}$ 67.34 (s) $C^{6,6'}$ 122.40 (s) $C^{4,4'}$ 126.19 (s) $C^{5,5'}$ 138.66 (s) $C^{3,3'}$ 150.76 (s) $C^{1,1'}$ 152.58 (s). Anal. Calcd for $C_{25}H_{38}CuIN_5O_3P$: C, 44.29; H, 5.65; N, 10.33. Found: C, 43.89; H, 5.40; N, 9.92%.

[CuI(phen)P(CH$_2$N(CH$_2$CH$_2$)$_2$NCH$_3$)$_3$] (1P). A CH_2Cl_2–cyclohexane (1 : 1 V : V) solution (20 mL) containing **1** (0.2065 g; 0.56 mmol), CuI (0.1061 g; 0.56 mmol) and phen (0.1105 g; 0.56 mmol) was stirred at room temperature for 3 h. The obtained red solution was filtered and evaporated to dryness. The orange solid was recrystallized from CH_2Cl_2–cyclohexane solution. Yield 74%. MS (acetone): (*m*/*z*) 613.3-[Cu(phen)P-(CH$_2$pipCH$_3$)$_3$]$^+$; 433.2-[CuP(CH$_2$pipCH$_3$)$_3$]$^+$; 423.1- [Cu(phen)$_2$]$^+$; 381.3; 371.3; 353.3. NMR (acetone-d$_6$): $^{31}P\{^1H\}$ (298 K): −33 (s*) ^1H (298 K): $H^{2,9}$ 9.32 (dd, J = 4.83, 1.42 Hz), $H^{4,7}$ 8.64 (dd, J = 8.24, 1.42 Hz), $H^{5,6}$ 8.12 (s), $H^{3,8}$ 7.97 (dd, J = 8.09, 4.69 Hz), $H^{3\text{-}P}$ 2.09 (s), $H^{1\text{-}P}$ 2.85 (s), $H^{2\text{-}P}$ 2.55 (s), $H^{4\text{-}P}$ 2.06(s) $^{13}C\{^1H\}$ (298 K): $C^{2,9}$ 150.61 (s), $C^{11,12}$ 143.95 (s), $C^{4,7}$ 137.38 (s), $C^{13,14}$ 130.10 (s), $C^{5,6}$ 127.66 (s), $C^{3,8}$ 125.51 (s), $C^{2\text{-}P}$ 55.99 (d, J = 5.77 Hz), $C^{1\text{-}P}$ 55.56 (d, J = 25.49 Hz), $C^{3\text{-}P}$ 55.83 (s), $C^{4\text{-}P}$ 46.18 (s). Anal. Calcd for $C_{30}H_{47}CuIN_8P$: C, 48.61; H, 6.39; N, 15.12. Found: C, 48.43; H, 6.80; N, 14.98%. Crystals of **1P**·$C_6H_5CH_3$ were obtained by slow evaporation of acetone–toluene solution.

[CuI(phen)P(CH$_2$N(CH$_2$CH$_2$)$_2$NCH$_2$CH$_3$)$_3$] (2P). A CH_2Cl_2–cyclohexane (1 : 1 V : V) solution (20 mL) containing **2** (0.1620 g; 0.40 mmol), CuI (0.0748 g; 0.40 mmol) and phen (0.0778 g; 0.40 mmol) was stirred at room temperature for 3 h. The obtained dark orange solution was filtered and evaporated to dryness under dinitrogen. The orange solid was recrystallized from acetone–cyclohexane solution. The obtained crystalline solid was filtered off and dried under vacuum. Yield 59%. MS(acetone): (*m*/*z*) 243.0-[Cu(phen)]$^+$; 353.3; 381.3; 413.3; 655.3-[Cu(phen)P-(CH$_2$pipC$_2$H$_5$)$_3$]$^+$;613.3; 475.3-[CuP(CH$_2$pipC$_2$H$_5$)$_3$]$^+$; 423.1-[Cu(phen)$_2$]$^+$. NMR (acetone-d$_6$): $^{31}P\{^1H\}$ (298 K): −33 (s*) ^1H (298 K): $H^{2,9}$ 9.35 (dd, J = 4.83, 1.42 Hz), $H^{4,7}$ 8.64 (dd, J = 8.24, 1.42 Hz), $H^{5,6}$ 8.12 (s), $H^{3,8}$ 7.97 (dd, J = 8.09,4.69), $H^{1\text{–}P}$ 2.85 (s*), $H^{2\text{–}P}$ 2.55 (s*), $H^{4\text{–}P}$ 2.19 (q, J = 7.38 Hz), $H^{3\text{–}P}$ 2.13 (s*), $H^{5\text{–}}$ 0.92 (t, J = 7.10 Hz); $^{13}C\{^1H\}$ (298 K): $C^{2,9}$ 150.69 (s), $C^{11,12}$ 143.97 (s), $C^{4,7}$ 137.38 (s), $C^{13,14}$ 130.13 (s), $C^{5,6}$ 127.66 (s), $C^{3,8}$ 125.51 (s), $C^{2\text{–}P}$ 56.22 (d, J = 5.77 Hz), $C^{1\text{-}P}$ 55.68 (d, J = 25.00 Hz), $C^{3\text{–}P}$ 53.56 (s), $C^{4\text{–}P}$ 52.69 (s), $C^{5\text{–}P}$ 12.50 (s). Anal. Calcd for $C_{33}H_{53}CuIN_8P$: C, 50.60; H, 6.82; N, 14.30. Found: C, 50.29; H, 6.80; N, 14.06%.

[CuI(phen)P(CH$_2$N(CH$_2$CH$_2$)$_2$O)$_3$] (3P). A mixture containing **3** (108.6 mg; 0.30 mmol), CuI (65.5 mg 0.30 mmol) and phen (68.2 mg; 0.30 mmol) was placed in a CH_2Cl_2–cyclohexane (1 : 1 V : V) solution (20 mL). The reaction mixture was stirred for 3 h. The precipitated orange solid was filtered off and washed with a small amount of CH_2Cl_2–cyclohexane (1 : 1 V : V) mixture. Yield 53%. MS (acetone): (*m*/*z*) 574.2-[Cu(phen)P(CH$_2$-morf)$_3$]$^+$; 512.0; 423.1-[Cu(phen)$_2$]$^+$; 332.2. NMR (acetone-d$_6$): $^{31}P\{^1H\}$ (298 K): -35 (s*) ^1H (298 K): $H^{2,9}$ 9.33 (dd, J = 4.75, 1.41 Hz), $H^{4,7}$ 8.67 (dd, J = 8.11, 1.54 Hz), $H^{5,6}$ 8.14 (s), $H^{3,8}$ 8.01 (dd, J = 8.11, 4.75 Hz), $H^{3\text{–}P}$ 3.36 (m, 4H), $H^{1\text{–}P}$ 2.87 (s, 2H), $H^{2\text{–}P}$ 2.54 (m, 4H) $^{13}C\{^1H\}$ (298 K): $C^{2,9}$ 150.77 (s), $C^{11,12}$ 143.96 (s), $C^{4,7}$ 137.63 (s), $C^{13,14}$ 130.25 (s), $C^{5,6}$ 127.86 (s), $C^{3,8}$ 125.76 (s), $C^{3\text{–}P}$ 67.34 (s), $C^{2\text{–}P}$ 56.66 (d, J = 4.9 Hz), $C^{1\text{–}P}$ 56.35 (d, J = 24.4 Hz).

Anal. Calcd for $C_{27}H_{38}CuIN_5O_3P$: C, 46.19; H, 5.45; N, 9.97. Found: C, 45.92; H, 5.27; N, 9.46%. Orange crystals of **3P**·0.5[Cu_2I_2(phen)$_2$] were obtained over several days by slow evaporation of CH_2Cl_2–toluene solution.

The antimicrobial activity

The antimicrobial activity was evaluated by the method of serial dilutions using the Antibiotic Broth (AB) (Dextrose 1.0; K_2HPO_4 3.68; Beef Extract 1.5; Peptone 5.0; KH_2PO_4 1.32; NaCl 3.5; Yeast Extract 1.5 g dm^{-3}), according to Grove and Randall.[45]

The following strains were employed: *Staphylococcus aureus* PCM 2054 (= ATCC 25923), *Escherichia coli* PCM 2057 (= ATCC 25922) from the Polish Collection of Microorganisms of the Institute of Immunology and Experimental Therapy in Wroclaw, as well as *Pseudomonas aeruginosa* and *Candida albicans* isolated from clinical samples. The two latter strains were identified using conventional methods and miniaturized identification systems (ID 32 C and API 20 NE [BioMérieux], respectively).

An overnight culture of the strain tested was diluted 1 : 1000 in the Antibiotic Broth (AB). To a series of tubes containing appropriate amounts of compounds (as the thin films on the walls of tubes), 0.9 ml of AB and 0.1 ml of microbial dilution were added. The following concentrations of each compound were obtained [mg ml^{-1}]: 2.56, 1.28, 0.64, 0.32, 0.16, 0.08. Drug-free purity controls and (for each strain) growth controls were included. The tubes were incubated at 37 °C for 24 h. The minimal inhibitory concentration (MIC) was defined as the lowest concentration of compound that inhibited microbial growth.

X-Ray crystallography

The data were collected at 100 K using a KM4-CCD diffractometer and graphite-monochromated Mo-Kα radiation generated from diffraction X-ray tube operated at 50 kV and 20 mA. The images were indexed, integrated, and scaled using the Oxford Diffraction data reduction package.[46] The structures were solved by direct methods using SHELXS97[47] and refined by the full-matrix least-squares method on all F2 data.[48] Non H atoms were included in the refinement, with anisotropic displacement parameters (except for the C46A atom in **1P**·$PhCH_3$ for which, due to poor crystal quality, isotropic displacement parameters were used) and the H atoms were included from the geometry of the molecules. The data were corrected for absorption;[46] min/max absorption coefficients are: for **1** (0.867/0.910), **3P**·0.5Cu_2I_2(phen)$_2$ (0.683/0.760), **3** (0.878/0.989), **1P**·$PhCH_3$ (0.678/0.876), **2** (0.876/0.910).

Crystal refinement data. **1** ≡ $C_{18}H_{39}N_6P$, M_r = 370.52, Monoclinic, Space Group $P2_1/c$ (No. 14), a = 7.214(2) Å, b = 24.228(3) Å, c = 12.995(3) Å, β = 107.46(2)°, V = 2166.6(8) Å^3, $D_c(Z = 4)$ = 1.136 g cm^{-3}, Mo-Kα radiation (λ = 0.71073 Å), μ_{Mo} = 0.140 mm^{-1}, specimen: 0.15 × 0.15 × 0.15 mm, T_{min} = 0.867, T_{max} = 0.910, θ_{max} = 37.00°, N_{total} = 39 696, N = 9523 (R_{int} = 0.0828), R_1 = 0.0504, wR_2 = 0.1249, S = 0.946, T = 100(2) K.

2 ≡ $C_{21}H_{45}N_6P$, M_r = 412.60, Trigonal, Space Group R3c (No. 161), a = 20.691(4) Å, b = 20.691(3) Å, c = 9.996(5) Å, V = 3706(2) Å^3, $D_c(Z = 6)$ = 1.109 g cm^{-3}, Mo-Kα radiation (λ = 0.71073 Å), μ_{Mo} = 0.129 mm^{-1}, specimen: 0.10 × 0.10 × 0.10 mm, Flack parameter[49]: −0.08(12) T_{min} = 0.876, T_{max} = 0.910, θ_{max} = 25.00°, N_{total} = 9762, N = 1306 (R_{int} = 0.0397), R_1 = 0.0270, wR_2 = 0.0643, S = 1.051, T = 100(2) K.

3 ≡ $C_{15}H_{30}N_3O_3P$, M_r = 331.39, Monoclinic, Space Group $P2_1/c$ (No. 14), a = 9.284(4) Å, b = 20.925(5) Å, c = 10.092(3) Å, β = 118.76(3)°, V = 1718.7(10) Å^3, $D_c(Z = 4)$ = 1.281 g cm^{-3}, Mo-Kα radiation (λ = 0.71073 Å), μ_{Mo} = 0.176 mm^{-1}, specimen: 0.18 × 0.15 × 0.11 mm, T_{min} = 0.878, T_{max} = 0.989, θ_{max} = 25.00°, N_{total} = 10 992, N = 3045 (R_{int} = 0.0819), R_1 = 0.0503, wR_2 = 0.1115, S = 0.947, T = 100(2) K.

1P·$C_6H_5CH_3$ ≡ $C_{37}H_{55}CuIN_8P$, M_r = 833.31, Triclinic, Space Group $P\bar{1}$ (No. 2), a = 12.799(3) Å, b = 18.400(4) Å, c = 19.828(4) Å, α = 64.78(4)°, β = 71.94(5)°, γ = 86.62(3)°, V = 4002(2) Å^3, $D_c(Z = 4)$ = 1.383 g cm^{-3}, Mo-Kα radiation (λ = 0.71073 Å), μ_{Mo} = 1.393 mm^{-1}, specimen: 0.18 × 0.17 × 0.15 mm, T_{min} = 0.678, T_{max} = 0.876, θ_{max} = 25.10°, N_{total} = 48915, N = 14193 (R_{int} = 0.1098), R_1 = 0.0984, wR_2 = 0.2727, S = 1.111, T = 100(2) K.

3P·0.5[Cu_2I_2(phen)$_2$] ≡ $C_{39}H_{46}Cu_2I_2N_7O_3P$, M_r = 1072.68, Triclinic, Space Group $P\bar{1}$ (No. 2), a = 9.675(3) Å, b = 10.196(5) Å, c = 23.342(4) Å, α = 83.32(3)°, β = 81.16(5)°, γ = 63.86(4)°, V = 2039.5(12) Å^3, $D_c(Z = 2)$ = 1.747 g cm^{-3}, Mo-Kα radiation (λ = 0.71073 Å), μ_{Mo} = 2.642 mm^{-1}, specimen: 0.10 × 0.12 × 0.15 mm, T_{min} = 0.683, T_{max} = 0.760, θ_{max} = 25.0°, N_{total} = 11161, N = 6684 (R_{int} = 0.0308), R_1 = 0.0351, wR_2 = 0.0799, S = 0.952, T = 100(2) K.

Conclusions

We prepared a series of the aliphatic, water soluble aminomethylphosphines and their complexes with copper(I) iodide and the diimine ligands. Our investigations indicate that even small changes in the structure of the phosphine ligands lead to some changes of the properties of their copper(I) complexes. The obtained complexes exhibit moderate luminescence in the solid state and promising biological activity. Due to the moderate stability of the investigated complexes in water solutions in air, in investigations of their biological activity, we cannot exclude the possibility of the decomposition of the complexes with dissociation of the phosphine ligand and oxidation of the copper centre, but the data shown indicate that biological activity of the investigated complexes also depends on the phosphine ligands.

The demonstrated convenient way of obtaining the new tris-(aminomethyl)phosphines may result in many new functionalized phosphines with a broad range of *N*-monosubstituted derivatives of piperazine. Commercially available piperazines of general formula H–N(CH_2CH_2)$_2$N–R (where –R, for example = –2-py, –CH_2OH, –$COCH_3$ –CO-2-py –$CH_2N(CH_3)_2$, –CH_2–2-pyrrole, –CH_2-2-furan) can bring new functionality and interesting properties to the phosphine ligands and their complexes.

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