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Extending the Application Scope of Organophosphorus(V) Compounds in Palladium(II) Pincer Chemistry

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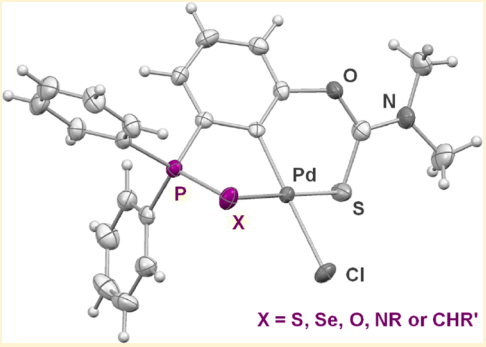
Supporting Information

ABSTRACT: 1-Dimethylthiocarbamoyloxy-3-diphenylphosphinobenzene was used as a key precursor for the synthesis of a whole series of organophosphorus(V) pincer ligands combining thiocarbamate donor group with P═X coordination arm, where X = S, Se, O, NR (R = Ph, 4-$NO_2C_6H_4$, COO^tBu, CH_2Ph) or CHR′ (R′ = COOEt, CN). Direct cyclopalladation of the ligands obtained (used either as individual compounds or generated *in situ* in the reaction mixture) afforded hybrid pincer complexes with five- and six-membered fused metallacycles. In the case of phosphine sulfide and phosphine selenide derivatives, the cyclopalladation can readily be accomplished in CH_2Cl_2 at room temperature, leading to the target pincer complexes in high yields. Their phosphine imide and phosphonium ylide counterparts can also be obtained under mild reaction conditions, but the yields strongly depend on the ligand stability (35−93%). Even in the case of the phosphoryl-functionalized ligand, the desired pincer-type complex was synthesized in ca. 15% yield, although the main direction of metalation was C(sp^3)−H bond activation of one of the methyl groups in $OC(S)NMe_2$ moiety. Realization of κ^3-*S,C,X*-coordination (X = S, Se, O, N, or C) in the resulting pincer complexes was unambiguously confirmed based on the multinuclear NMR (^1H, ^{13}C, ^{31}P, and ^{77}Se) and IR spectroscopic data. Comparative single-crystal XRD analyses allowed for outlining the main structural features of the palladacycles obtained depending on the nature of ancillary P(V)-donor group. In addition, the possibility of solid-phase cyclopalladation was demonstrated by the examples of phosphine chalcogenide and stable phosphine imide ligands. In most cases, this approach afforded the desired complexes with the same or even higher efficiencies than the conventional solution-based method. Preliminary investigations on the cytotoxic activity of some of the complexes obtained against several human cancer cell lines revealed the high activity of phosphine imide-based palladacycles, rendering further studies in this field promising.



INTRODUCTION

Organophosphorus compounds comprise one of the most important ligands in organometallic and coordination chemistry, playing an essential role in homogeneous catalysis and different metal separation processes. In particular, they are widely used in the synthesis of the so-called pincer complexes bearing specific tridentate monoanionic ligands, which have emerged as a privileged class of organometallic compounds owing to structural diversity and multiple applications.[1,2] Many pincer complexes containing phosphine, phosphinite, phosphite, and other P(III)-donors proved to be active (pre)-catalysts in different chemical reactions, convenient models for investigation of strong bond activation and metal−ligand cooperation, building blocks for metallodendrimers and complicated nanostructures and remain the subjects of continuous studies.[3] At the same time, the potential of their P(V)-counterparts seems to be substantially underestimated. Over recent years, the pincer chemistry of organothiophosphorus(V) compounds, mainly phosphine sulfides, has evolved as an attractive research area, giving rise to a range of complexes with promising luminescence properties, intriguing chemical behavior as well as remarkable catalytic performance in different processes (see selected examples with platinum group metals in Figure 1). Their syntheses and properties were summarized in several reviews.[4]

As for the other phosphine chalcogenide derivatives, a literature survey has revealed only a few examples of Pd(II) and Pt(II) pincer complexes with the coordinated phosphoryl group (Figure 2).[5] Nevertheless, this result was expected given the hard donor nature of the oxygen atom.[6] Complexes **I**[7] and **II**[8] were smoothly synthesized by direct cyclopalladation of the

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Organometallics XXXX, XXX, XXX–XXX

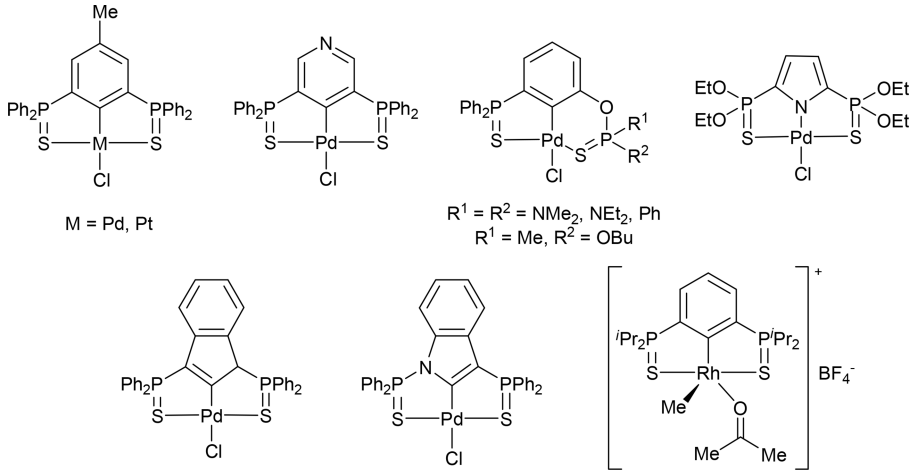

Figure 1. Pincer complexes of platinum group metals with organothiophosphorus(V) ligands.

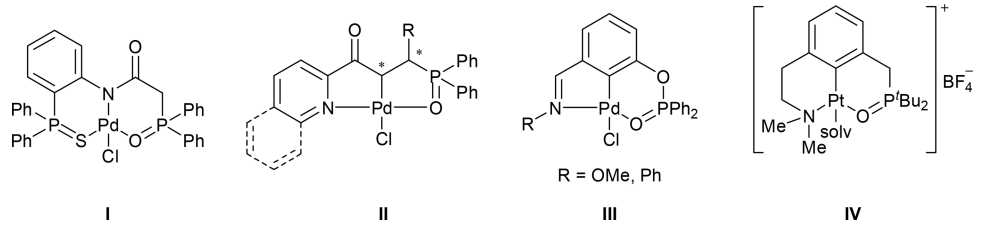

Figure 2. Noble metal pincer complexes with the pendant phosphoryl arm.

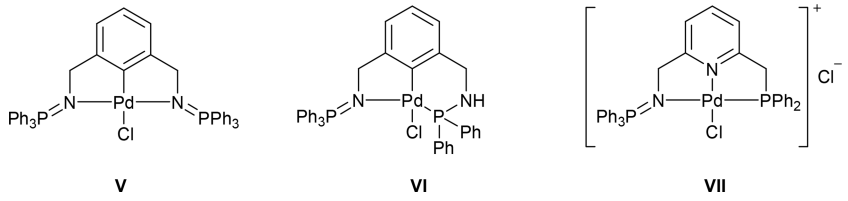

Figure 3. Palladium(II) pincer complexes with phosphine imide ligands.

corresponding functionalized amide or ketone. At the same time, their arene-based counterparts **III**[9] and **IV**[10] cannot be obtained by activation of the ligand C(sp^2)−H bond and were derived only from the preliminary coordinated (metalated) precursors as a result of oxygenation of the thiophosphoryl-substituted predecessor or oxidation of the corresponding κ^3-*P,C,N*-phosphine complex, respectively. To the best of our knowledge, there are no pincer complexes with selenophosphoryl ligands.[11]

Surprisingly, despite the popularity of *N*-donor pincer ligands, a very limited number of related Pd(II) complexes with the coordinated P═N group has been reported to date. In fact there is only one symmetrical palladium(II) *N,C,N*-pincer complex based on a bis(phosphine imide) ligand with a central benzene core (compound **V**, Figure 3), which was designed to provide a pocketing effect for a metal center by the exocyclic Ph_3P═N groups.[12] The noninnocent behavior of the same ligand upon metalation resulted in an unsymmetrical pincer complex **VI** combining phosphine imide and aminophosphine donor groups. Recently, a parent cationic complex with a central pyridine ring was also synthesized (compound **VII**).[13] It should be noted that a range of functionalized aryl-substituted phosphine imides afforded κ^3-*C,N,*X-palladacycles (X = S, P, N, and O) with either endo- or exocyclic P═N groups, which also display tridentate monoanionic coordination.[14] However, unlike the classical pincer compounds, these complexes feature *cis*-arrangement of ancillary donor groups, since the metalated benzene rings are shifted aside. These structural differences inevitably affect the system properties, including its tunability and reactivity. Finally, despite the flourishing chemistry of monometallacyclic complexes derived from phosphonium ylides,[15,16] there are no pincer or related Pd(II) complexes with tridentate monoanionic ligands having R_3P═CR′R″ ancillary donor groups.

Taking into account the fairly limited data on the use of pentavalent phosphorus compounds in the synthesis of pincer complexes, it seemed interesting to obtain a whole series of ligands bearing phosphine sulfide, selenide, oxide, imide, and phosphonium ylide donor groups and to explore the possibility of their direct cyclopalladation. Herein, we report on the synthesis of new pincer ligands bearing different P(V)-donor groups from a single key precursor and peculiarities of their direct cyclopalladation both under conditions of conventional solution-based method and in the absence of a solvent according to the solid-phase methodology recently developed by our group.[17] The results of comparative XRD analyses and preliminary investigations on cytotoxic activity of the palladacycles obtained are also discussed.

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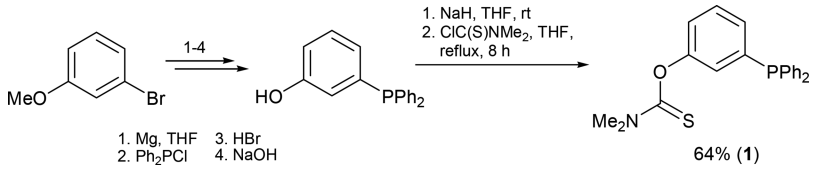
Organometallics XXXX, XXX, XXX−XXX

Scheme 1. Synthesis of Key Thiocarbamoyloxy-Substituted Phosphine 1

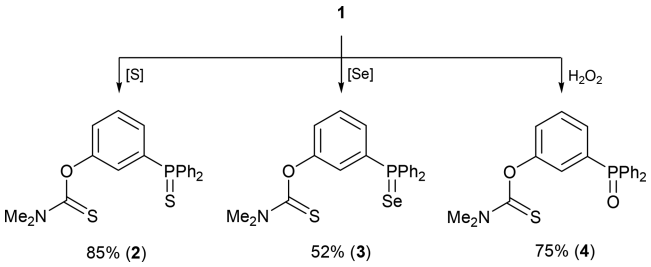


RESULTS AND DISCUSSION

Synthesis of Pincer Complexes in Solution. A convenient key precursor for the synthesis of pincer ligands with different P(V)-donor groups appeared to be thiocarbamoyloxy-substituted phosphine **1**. It is readily available from the reaction of a sodium salt of 3-(diphenylphosphino)phenol with $ClC(S)NMe_2$ in THF under reflux (Scheme 1). In turn, the phosphine-functionalized phenol was synthesized starting from 3-bromoanisole according to the published procedure.[18] Compound **1** was isolated as a crystalline solid in a good yield after simple recrystallization. Although phosphine **1** is gradually oxidized in solution (ca. 20% of the corresponding phosphine oxide in $CDCl_3$ in 1 day), it is quite stable to atmospheric oxygen in the solid state and can be stored without notable oxidation for several months. For a long period of time, there has been no data on pincer derivatives with thiocarbamate donor groups. Recently, bis(dimethylthiocarbamoyloxy)benzene was shown to serve as an efficient extractant for Pd(II) ions from an automotive catalyst leach liquor.[19] Its high performance was associated with the rapid and selective cyclometalation resulting in a pincer-type palladacycle. Furthermore, a bis(thiocarbamate) Pd(II) pincer complex immobilized on fibrous nanosilica (KCC-1) demonstrated high catalytic activity in the synthesis of 3-sulfenylindoles with excellent recyclability.[20] The choice of the thiocarbamate donor moiety as the preformed coordination arm was also supported by our recent results on the successful cyclopalladation of a symmetrical bis(thiocarbamate) pincer ligand not only in solution but also in the absence of a solvent under conditions of mechanochemical activation.[17c]

The reactions of phosphine **1** with elemental sulfur and selenium as well as H_2O_2 smoothly afforded corresponding phosphine chalcogenides **2**–**4** (Scheme 2). This route was

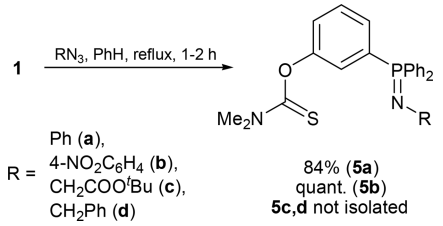
Scheme 2. Synthesis of Phosphine Chalcogenides 2–4



preferred to alternative reactions of 3-diphenylphosphoryl-,[18] 3-diphenylthiophosphoryl-[18,21] or 3-diphenylselenophosphoryl-substituted[22] phenols with $ClC(S)NMe_2$ due to the higher efficiency. Thus, the yield of ligand **4** derived from P(O)-substituted phenol appeared to be substantially lower than that observed upon oxidation of **1** (50 vs 75%). This was caused by the complicated separation from the unreacted phenol and reduced nucleophilicity of the phosphorylated phenolate anion compared to its P(III)-counterpart.

Phosphine imide analogs of ligands **2**–**4** were readily derived from the reactions of key phosphine **1** with a range of organic azides (Scheme 3). The stability of the resulting

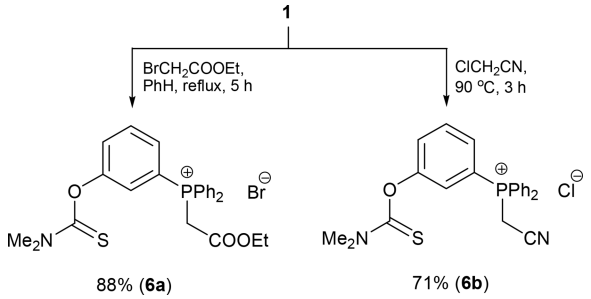
Scheme 3. Synthesis of Phosphine Imides 5a–d



compounds strongly depended on the nature of a substituent at the nitrogen atom of the P═N moiety. Thus, aromatic derivatives **5a**,**b** appeared to be quite stable to the residual moisture and were isolated in high yields. At the same time, their aliphatic counterparts, **5c**,**d**, readily hydrolyzed and were used for the synthesis of pincer complexes without isolation (*vide infra*).

Finally, treatment of phosphine **1** with ethyl bromoacetate or chloroacetonitrile led to phosphonium salts **6a**,**b**, convenient precursors for phosphonium ylide ligands (Scheme 4).

Scheme 4. Synthesis of Phosphonium Salts 6a,b



Dehydrohalogenation of compounds **6a**,**b** can easily be accomplished under action of Et_3N, but the resulting ylide derivatives are prone to hydrolysis and as in the case of phosphine imides **5c**,**d** were generated *in situ* for complexation with Pd(II) ions.

The structures of ligands and ligand precursors **2**–**6** were unambiguously confirmed by the NMR and IR spectroscopic data. In particular, the ^{31}P NMR spectra of **2** and **4**–**6** show singlet signals in the regions characteristic for these classes of organophosphorus compounds: δ_P = 42.92 (phosphine sulfide **2**), 28.48 (phosphine oxide **4**), −1.20 and 4.50 (phosphine imides **5a** and **5b**, respectively), and 20.66 and 21.77 ppm (phosphonium salts **6a** and **6b**, respectively). In the ^{31}P NMR spectrum of phosphine selenide **3**, the typical selenium satellites are observed with the coupling constant $^1J_{PSe}$ =

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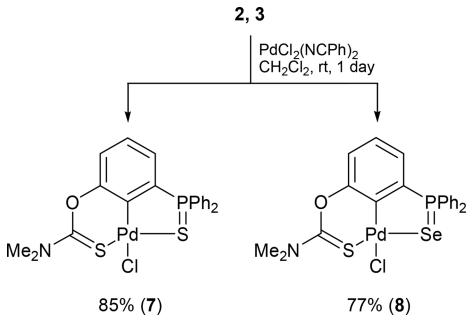
Organometallics XXXX, XXX, XXX−XXX

734.0 Hz (δ_P = 34.88 ppm). The ^{1}H NMR spectra of compounds **2**–**6** display the singlet resonances of the thiocarbamate hydrogen nuclei at ca. 3.30–3.40 or 2.50–2.90 ppm depending on the solvent in use along with the signals of the other aliphatic and aromatic protons. Most of the signals in the ^{13}C NMR spectra of the ligands and ligand precursors obtained were unambiguously assigned to the certain carbon nuclei (*vide infra*).

Studying the complexing features of the ligands obtained toward Pd(II) ions, it was found that phosphine sulfide and selenide derivatives **2** and **3** readily undergo direct cylopalladation upon interaction with $PdCl_2(NCPh)_2$ in dichloromethane at room temperature, affording pincer complexes **7** and **8** in high yields (Scheme 5). A drastic

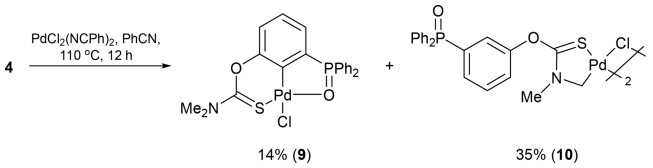
Scheme 5. Synthesis of Pincer Complexes 7 and 8



change in the color of reaction mixtures from dark-red to yellow observed already in the first 30 min was indicative of the rapid cyclometalation process,[23] although the reactions were left to complete for 1 day. Compound **8** appeared to be the first example of a selenophosphoryl pincer complex.

While good results were predictable on direct cyclopalladation of ligands **2** and **3**, bearing soft ancillary donor centers, we actually did not expect to obtain the related palladacycle based on P(O)-functionalized ligand **4**. As stated above, there are only several examples of cyclopalladated and cycloplatinated complexes with the coordinated phosphoryl group (Figure 2), and neither of the arene-based complexes was obtained by direct cyclometalation. Nevertheless, the ^{31}P NMR monitoring of the reaction of ligand **4** with $PdCl_2(NCPh)_2$ under mild conditions (dichloromethane, room temperature) revealed the formation of a product with δ_P = 61.5 ppm. Even though in 1 month this product was still observed only in trace amounts, such a strong downfield shift of the phosphorus resonance relative to that of the free ligand ($\Delta\delta_P \sim 33$ ppm) was undoubtedly indicative of complex formation. The reaction performed under harsh conditions (prolonged heating in benzonitrile) allowed us to increase the yield of this product and isolate it in an individual form. Surprisingly, it indeed appeared to be pincer complex **9** featuring κ^3-*S,C,O*-coordination (Scheme 6). Furthermore, purification by column chromatography afforded another cyclopalladated product—dimeric complex, **10**, which resulted from the metalation of one of the methyl groups at the nitrogen atom. The yield of isolated product **10** was at least twice that of pincer complex **9**. The preferential activation of the C(sp^3)–H bond over the C(sp^2)–H bond can be rationalized both by the harsh reaction conditions and by the presence of the unfavorable hard oxygen ancillary donor. However, the unprecedented direct cyclopalladation of the

Scheme 6. Cyclopalladation of Phosphoryl-Substituted Ligand 4



phosphine oxide ligand is an example of the rich coordination potential of pincer systems.

The reactions of phosphine imides **5a,b** with $PdCl_2(NCPh)_2$ in the presence of Et_3N under mild conditions afforded desired pincer-type complexes **11a,b** in moderate to good yields (Scheme 7, method A). Their counterparts, bearing aliphatic substituents at the nitrogen atom of the P=N moiety (compounds **11c,d**), were obtained upon interaction of the same Pd(II) precursor with the corresponding phosphine imides generated *in situ* in the reaction mixtures without ligand isolation (Scheme 7, method B). Interestingly, the yields of complexes **11a,b** synthesized by method B were slightly higher than those in the reactions with the preformed ligands (method A). This makes a two-step, one-pot methodology more attractive even in the case of stable phosphine imide derivatives.

The suggested methodology appeared to be efficient also for the synthesis of phosphonium ylide pincer complexes. Thus, the reactions of $PdCl_2(NCPh)_2$ with phosphonium ylides, obtained upon treatment of **6a,b** with an excess of Et_3N, in benzene–CH_2Cl_2 gave desired κ^3-*S,C,C*-palladacycles **12a,b** (Scheme 8). Interestingly, in the case of phosphonium bromide precursor **6a**, the product isolated upon purification by column chromatography appeared to be bromide complex **12a-Br**, although the cyclopalladation should result in a mixture of chloride (**12a-Cl**) and bromide (**12a-Br**) derivatives. Indeed, the ^{31}P NMR spectrum of the reaction mixture before purification demonstrated two singlet signals at ~23.4 and 21.8 ppm in 1:1 ratio. When Et_3NHBr resulting from the dehydrohalogenation of the starting phosphonium salt was removed from the reaction medium by filtration, the expected chloride derivative (complex **12a-Cl**) was isolated. Although the preference of formation is still unclear (that of the bromide derivative upon purification by column chromatography instead of the expected chloride complex with the smaller anion), the halide ligand in complex **12a** was shown to be readily displaced in both directions in the presence of excess tetralkylammonium salts (Scheme 9).

Spectroscopic Characterization of the Cyclopalladated Complexes. The realization of κ^3-*S,C,X*-coordination (X = S, Se, O, N, or C) in complexes **7**–**9**, **11**, and **12** was unambiguously confirmed based on the multinuclear NMR (^{1}H, ^{13}C, ^{31}P, and ^{77}Se) and IR spectroscopic data. The compositions of most of the complexes were supported by elemental analyses. A strong downfield shift of the phosphorus resonances in the ^{31}P NMR spectra of almost all the pincer complexes obtained compared to those of the free ligands evidences the coordination of the P(V)-ancillary donor group. The value of $\Delta\delta_P$ ranges from 2.0 to 43.5 ppm and strongly depends on a particular class of organophosphorus compounds. Thus, the smallest differences of the ^{31}P NMR resonances were detected for the phosphonium ylide derivatives (the broadened signals of free phosphonium ylides generated from salts **6a** and **6b** in C_6D_6 were observed at 18.20

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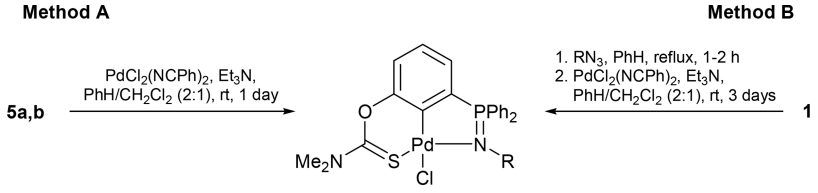
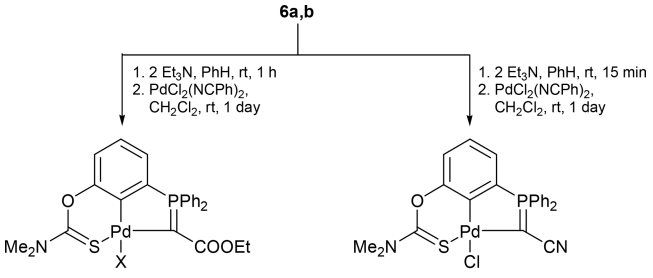
Organometallics XXXX, XXX, XXX–XXX

Scheme 7. Synthesis of Phosphine Imide Pincer Complexes 11a–d



R = Ph: 83% (method A), 93% (method B) (**11a**);
4-$NO_2C_6H_4$: 57% (method A), 66% (method B) (**11b**);
CH_2COO^tBu: 35% (**11c**); CH_2Ph: 45% (**11d**)

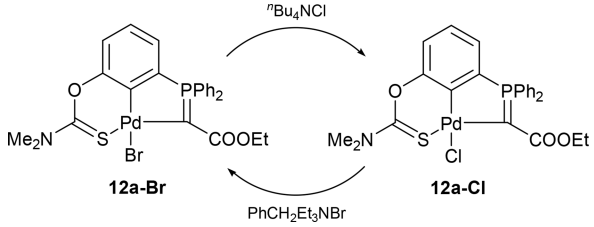
Scheme 8. Synthesis of Phosphonium Ylide Pincer Complexes 12a,b



X = Br: 72% (**12a-Br**)
X = Cl: 41% (**12a-Cl**)

54% (**12b**)

Scheme 9. Interconversion of Bromide and Chloride Complexes 12a



and 22.65 ppm, respectively). For phosphine sulfide derivatives **2** and **7**, $\Delta\delta_P$ composed 5.6 ppm. A close displacement ($\Delta\delta_P$ = 4.6 ppm) was observed for their selenophosphoryl counterparts, but the complexation led to an upfield shift of the phosphorus resonance. At the same time, the signal of the selenium nucleus in the ^{77}Se NMR spectrum of palladacycle **8** appeared to be strongly deshielded upon coordination ($\Delta\delta_{Se}$ = 256.80 ppm). Finally, the greatest differences were registered for phosphine oxide and phosphine imide derivatives, reaching up to 43.5 ppm for the phosphine imide complex bearing the benzyl substituent at the nitrogen atom of the P═N moiety. The IR and Raman spectra of the compounds under consideration also unequivocally testify to the complexation of the P═X donor group by the lower frequency displacement of the corresponding stretching vibrations. Depending on the substituent X, they were observed in the spectra of the complexes at 608/625, 566, 1126, 1270–1280, and 830–860 cm^{-1} for X = S, Se, O, NR, and CHR, respectively.

The coordination of the thiocarbamate donor group is confirmed by the higher frequency shift of the characteristic NC(S)O stretching vibrations in the IR spectra of all the palladacycles obtained, typically from a broadened absorption band with medium intensity at ca. 1540 cm^{-1} to a strong band in the range of 1550–1560 cm^{-1}. It is also reflected in an upfield shift of the signals of C═S carbon nuclei in the ^{13}C NMR spectra of the resulting complexes compared to those of the free ligands ($\Delta\delta_C$ = 8.5–10.5 ppm).

The occurrence of metalation of the central benzene ring can be inferred from a reduction of the total integral intensity of the aromatic protons by 1H in the ^{1}H NMR spectra of complexes **7**–**9**, **11**, and **12** relative to the spectra of free ligands. In the case of phosphoryl-functionalized pincer complex **9**, the remaining three protons of the aromatic core appear as well-defined separate signals with the expected multiplicities. As for the ^{13}C NMR spectra of the palladacycles obtained, the most drastic changes are observed for the signals of C2 and C3 carbon nuclei of the central benzene ring. They appear to be substantially downfield shifted compared to the signals of the free ligands (up to $\Delta\delta_C \sim 24$ ppm), which testifies the change in electronic properties of the ancillary P(V)-donor groups upon coordination by Pd(II) ions. Besides a strong downfield shift ($\Delta\delta_C$ = 7.57–14.47 ppm), the signals of the C2 carbon nuclei changed their polarity, thereby confirming the metalation. The signals of other carbon nuclei

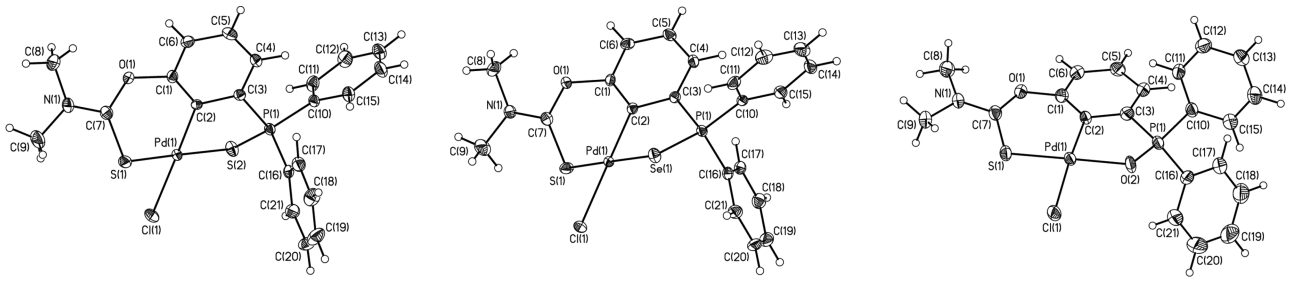


Figure 4. General views of phosphine chalcogenide complexes **7** (a), **8** (b) and **9** (c). Solvate molecules of CH_2Cl_2 and EtOH (**7**), CH_2Cl_2 (**8**), and $CHCl_3$ (**9**) are omitted for clarity. The second symmetry-independent molecule of palladacycle **9** is not shown. Hereinafter, the atoms are presented as thermal ellipsoids at 50% probability level.

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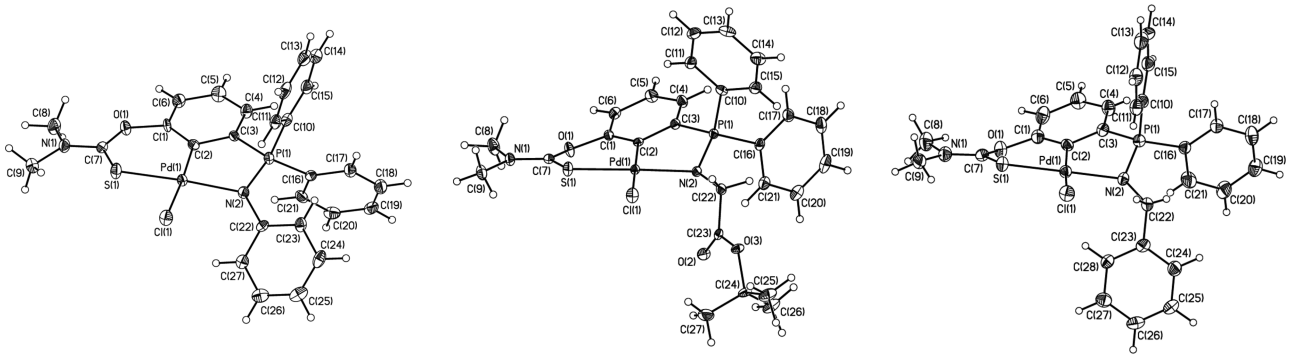
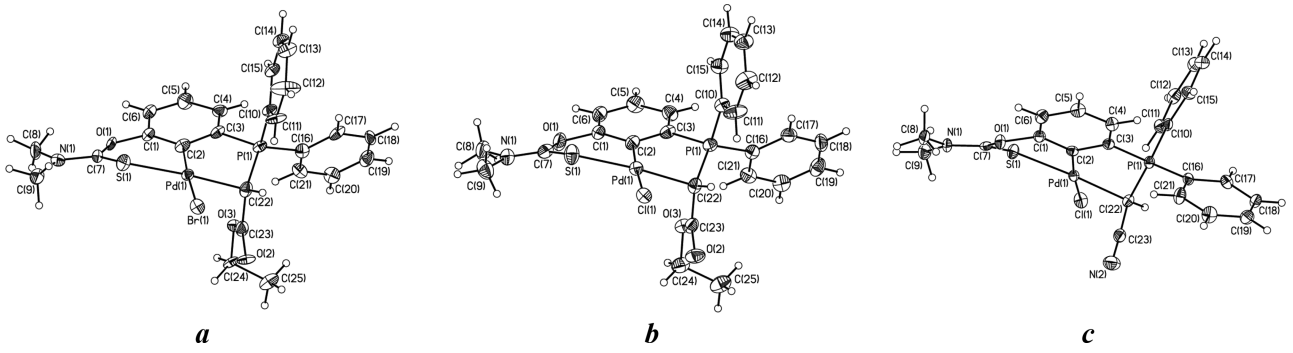
Organometallics XXXX, XXX, XXX–XXX



a *b* *c*

Figure 5. General views of phosphine imide complexes **11a** (a), **11c** (b) and **11d** (c). Solvate molecules of $CHCl_3$ (**11c**) and CH_2Cl_2 (**11d**) as well the second symmetry-independent molecules of palladacycles **11a** and **11d** are not shown.



a *b* *c*

Figure 6. General views of phosphonium ylide complexes **12a-Br** (a), **12a-Cl** (b) and **12b** (c). Solvate EtOH molecules (**12b**) are omitted for clarity.

are also indicative of pincer complex formation (see the Experimental Section). Note that 2D NMR spectroscopy (COSY, HMQC, and HMBC pulse sequences) allowed us to fully assign the signals of selenophosphoryl-functionalized ligand **3** and its complex **8** (Figures S1–S14). The results obtained were used for interpretation of the NMR spectra of the other compounds from this study (see the Experimental Section and Figures S15–S29).

As for dimeric κ^2-*C*,*S*-palladacycle **10**, a singlet signal of the phosphorus nucleus in the ^{31}P NMR spectrum was observed in the region typical for noncoordinated phosphine oxides (27.98 ppm vs 28.48 ppm in the case of complex **10** and ligand **4**, respectively). The characteristic stretching vibrations of the P═O bond in the IR and Raman spectra were also observed in the region of free tertiary phosphine oxides. Furthermore, the aromatic hydrogen and carbon nucleus patterns in the ^1H and ^{13}C NMR spectra resemble those of ligand **4**, while the signals of the aliphatic moiety appear as two singlets with the intensities of 6H and 4H (δ_H = 3.14 and 3.82 ppm, respectively) and different polarities (δ_C = 40.13 and 41.39 ppm), which is consistent with the presence of NMe and NCH_2Pd groups.

X-ray Diffraction Studies. Complexes **7**–**9**, **11a**, **11c**, **11d**, **12a-Br**, **12a-Cl**, and **12b** were characterized by single-crystal X-ray diffraction (Figures 4–6). Table 1 lists selected bond distances and angles for these compounds. In all cases, the four-coordinate palladium center adopts a slightly distorted square-planar geometry. In general, the Pd(1)–C(2) and Pd(1)–Cl(1) (or Pd(1)–Br(1) in the case of **12a-Br**) distances are within the expected norms for these types of complexes. Furthermore, the geometric parameters of the coordinated thiocarbamate group lie within the ranges observed earlier for symmetrical pincer prototypes.[17c,19] However, the presence of different donor centers in the P(V)-coordination arm inevitably results in structure variations, and some of the tendencies revealed merit further discussion. First of all, the lengths of the coordinated P═X bonds strongly depend on the nature of substituent X and reduce in the following sequence: Se > S > C > N > O, from 2.1556(10) Å for phosphine selenide derivative **8** to 1.511(4) Å for phosphine oxide complex **9**. The P═S distances are in reasonable agreement with the published values for the previously reported pincer complexes.[21,23,24] For phosphine selenide and phosphonium ylide derivatives a comparison was possible only with the monopalladacyclic species (see refs 11 and 16c,e,g,i,k,l, respectively) and did not reveal considerable differences. For example, the P═C distances in the related monometallacyclic Pd(II) complexes derived from different phosphonium ylides lie within a narrow range of 1.772–1.793 Å,[16c,e,g,i,k,l] whereas the corresponding values for the pincer complexes described in this work are 1.760–1.772 Å. Unexpectedly, the P═N distances in compounds **11a**, **11c**, and **11d** appeared to be closer to those in pincer complexes **V**–**VII** (Figure 3) featuring exocyclic phosphine imide groups[12,13] (1.593–1.603 Å) rather than to those in κ^3-*C*,*N*,X-palladacycles with endocyclic P═N groups derived from aryl-substituted phosphine imides[14d,f,h,i] (1.617–1.649 Å). The presence of different donor centers in the P═X group slightly affects the lengths of coordinative bonds between the palladium atom and the sulfur atom of the thiocarbamate moiety, which reduce in the above-mentioned order (Se, S, C, N, O), with the variation reaching up to 4%. A more marked

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Organometallics XXXX, XXX, XXX–XXX

Table 1. Selected Bond Distances (Å) and Angles (deg) for Complexes 7−9, 11a, 11c, 11d, 12a-Br, 12a-Cl, and 12b

			9		11a			11d				
	7	8	9(A)	9(B)	11a(A)	11a(B)	11c	11d(A)	11d(B)	12a-Br	12a-Cl	12b
Pd(1)−S(1)	2.2932(9)	2.3027(9)	2.2106(14)	2.2107(14)	2.2461(11)	2.2515(11)	2.2497(5)	2.2384(12)	2.2339(12)	2.297(4)	2.2840(14)	2.2869(10)
Pd(1)−C(2)	1.981(3)	1.982(3)	1.985(5)	1.980(5)	1.975(4)	1.971(4)	1.9770(19)	1.972(4)	1.962(4)	2.021(12)	1.990(5)	1.982(4)
Pd(1)−Cl(1)[a]	2.3974(9)	2.3915(9)	2.3793(14)	2.3819(14)	2.4018(11)	2.3980(11)	2.4124(5)	2.3796(12)	2.3746(13)	2.5099(15)	2.4061(11)	2.3900(9)
Pd(1)−X	2.3587(9)	2.4564(4)	2.105(4)	2.092(4)	2.099(3)	2.088(3)	2.0713(16)	2.055(3)	2.051(4)	2.116(12)	2.117(5)	2.104(4)
P(1)−X	2.0029(13)	2.1556(10)	1.514(4)	1.511(4)	1.609(4)	1.599(4)	1.6030(17)	1.576(4)	1.572(4)	1.760(12)	1.765(5)	1.772(4)
C(7)−S(1)	1.700(4)	1.697(3)	1.703(6)	1.698(6)	1.692(4)	1.696(4)	1.696(2)	1.685(5)	1.680(5)	1.672(13)	1.689(5)	1.696(4)
C(7)−O(1)	1.336(5)	1.340(4)	1.324(7)	1.333(6)	1.328(5)	1.333(5)	1.332(2)	1.337(5)	1.321(5)	1.308(15)	1.328(6)	1.339(4)
C(1)−O(1)	1.415(4)	1.421(4)	1.384(7)	1.406(6)	1.398(5)	1.400(5)	1.402(2)	1.385(5)	1.406(5)	1.350(15)	1.401(6)	1.401(4)
C(7)−N(1)	1.311(5)	1.308(4)	1.322(7)	1.312(7)	1.327(5)	1.319(5)	1.326(2)	1.303(6)	1.311(6)	1.355(16)	1.309(7)	1.322(5)
C(2)−Pd(1)−Cl(1)[a]	178.98(10)	178.09(10)	174.10(16)	174.98(15)	174.43(12)	172.40(12)	173.11(6)	170.15(13)	171.60(13)	175.6(4)	175.65(15)	173.87(11)
S(1)−Pd(1)−X	178.06(4)	179.18(3)	176.80(13)	177.05(11)	176.21(10)	174.83(10)	177.75(5)	177.55(10)	176.82(11)	176.5(4)	175.78(14)	177.03(11)
C(2)−Pd(1)−S(1)	89.35(10)	89.45(10)	94.48(16)	94.58(16)	94.29(12)	93.45(13)	93.12(6)	93.04(13)	93.29(13)	91.9(4)	92.73(15)	92.91(11)
S(1)−Pd(1)−Cl(1)[a]	89.68(3)	89.01(3)	87.42(5)	88.12(5)	83.37(4)	86.28(4)	87.844(19)	88.41(4)	87.90(5)	89.55(10)	88.90(5)	88.93(4)
Cl(1)−Pd(1)−X	90.71(3)	90.88(2)	90.31(11)	89.54(11)	96.20(10)	94.75(10)	93.32(5)	93.78(10)	94.56(11)	90.1(3)	89.89(13)	90.97(10)
X−Pd(1)−C(2)	90.28(10)	90.63(10)	87.99(19)	87.89(18)	86.47(15)	86.20(16)	85.96(7)	84.99(16)	84.57(17)	88.7(5)	88.76(19)	87.49(15)
φ	31.10	33.21	11.44	8.43	9.17	15.70	18.84	22.79	21.71	19.57	19.54	22.71

[a]Br(1) atom instead of Cl(1) for complex **12a-Br**

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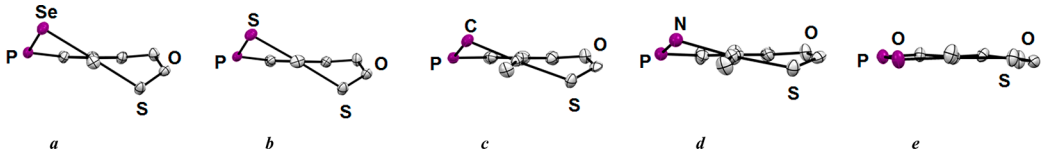


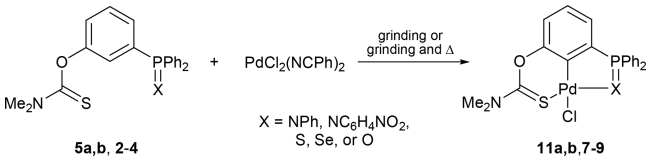
Figure 7. Relative disposition of the mean planes formed by the central benzene ring and palladium square in complexes **8** (a), **7** (b), **12b** (c), **11a(B)** (d), and **9(B)** (e).

effect was observed on the conformations of the resulting fused palladacycles. The six-membered metallacycle involving sulfur atom of the thiocarbamate group features either twist or distorted boat conformation. In general, the deviations of different pairs of atoms (Pd(1)/C(1), S(1)/C(1), or S(1)/O(1)) reduce depending on the substituent X in the P═X group from Se to S, then to C, N, and O. A conformation of the five-membered metallacycle including P═X donor group also changes in the same manner: from twist in the case of phosphine selenide complex **8** to a flattened envelope in the case of phosphine oxide derivative **9**. The described structural features can be better presented by variation of the twist angle (φ) between the plane of the central benzene core (C(1)–C(6) mean plane) and palladium square (Pd(1)S(1)Cl(1)-C(1)X mean plane) (Table 1). Figure 7 depicts this flattening effect on going from the larger atom X to the smaller ones.

Solid-Phase Cyclopalladation. Solid-phase methodologies are deeply embedded in the synthesis of different biomolecules and inorganic materials and are increasingly used in the preparation of small organic molecules.[25] At the same time, their potential in the field of organometallic synthesis is still largely untapped.[26] Although the first attempts to advance and simplify cyclometalation, one of the most important fundamental organometallic transformations, using solvent-free strategies date back to the 1970s,[27] before our investigations[17] they have never been applied to the synthesis of such an exciting class of compounds as pincer complexes. We have demonstrated that solid-phase cyclopalladation can serve as an efficient and green alternative to the conventional synthesis of pincer complexes in solution: simple heating of homogenized mixtures of a ligand and appropriate Pd(II) precursor,[17d] obtained by manual grinding of the reactants in a mortar, readily afforded pincer-type complexes with benzothiazole and thiophosphoryl coordination arms.[17e] Subsequently, this strategy proved its efficiency in yielding several series of *C*- and *N*-metalated pincer complexes having ancillary *S*- and *N*-donor groups.[17] In most cases, grinding was used only to thoroughly mix the reagents. However, recently we have shown that this kind of mechanical force can promote cyclopalladation on its own. Thus, a symmetrical bis(thiocarbamate) ligand was selectively and completely cyclometalated with $PdCl_2(NCPh)_2$ upon grinding of the reactants in a mortar and, more importantly, in a vibration ball mill at gram scale.[17c] Taking this into account, it seemed interesting to adopt the solid-phase approach to the hybrid thiocarbamate pincer ligands bearing different ancillary P(V)-donor groups.

Unfortunately, phosphonium ylides and phosphine imides bearing aliphatic substituents at the nitrogen atom of the P═N group, which are not stable in the solid state in air, cannot be used as starting materials for investigation of the possibility of solid-phase cyclopalladation. Nevertheless, the formation of target pincer complexes under solvent-free conditions was observed in the case of aryl-substituted phosphine imides **5a,b** (Table 2, entries 1,2). It is important to note that whereas the

Table 2. Solid-Phase Cyclopalladation of the Hybrid Thiocarbamate Pincer Ligands Bearing Different Ancillary P(V)-Donor Groups



entry	ligand	product	conditions	yield
1	**5a**	**11a**	rt, 1 day	49%
2	**5b**	**11b**	60–65 °C, 5 min	50%
3	**2**	**7**	75–80 °C, 5 min	quant.
4	**3**	**8**	105–110 °C, 5 min	quant.
5	**4**	**9**	90 °C, 10 min	10%

reaction in a homogenized mixture of ligand **5b** with $PdCl_2(NCPh)_2$ requires heating at 60–65 °C for 5 min, the solid-phase cyclopalladation of its counterpart **5a** proceeds already at room temperature owing to the mechanochemical activation achieved by grinding without any external energy supply. However, in both cases, no evolution of HCl was detected, although it is a characteristic feature of solid-phase cyclometalation with $PdCl_2(NCPh)_2$.[17c,d] The ^{31}P NMR spectra of the solid residues obtained in the experiments with **5a,b** (in $CDCl_3$) demonstrated two main singlet signals in ~1:1 ratio, one of which corresponds to the desired pincer complex (δ_P = 41.54 (**5a**) and 41.11 (**5b**) ppm), and the second one is characteristic of a phosphine oxide derivative (δ_P = 31.24 (**5a**) and 31.87 (**5b**) ppm). The latter is likely to result from partial hydrolysis of the ligand promoted by HCl liberated upon cyclometalation of the phosphine imides. This assumption is in good agreement with the observed yields of the target pincer complexes – ~ 50% in both cases. Note that the reactions of these ligands with $PdCl_2(NCPh)_2$ in solution in the absence of a base were also accompanied by partial hydrolysis of the ligand. To exclude the formation of pincer complexes **11a,b** upon dissolution in $CDCl_3$, the solid residues obtained after the experiments without any workup were analyzed by IR and Raman spectroscopies, which provide fast and valuable methods for monitoring solid-state reactions[17] (Figures S30–S39). The registered spectra revealed along with the characteristic absorption bands of the pincer complexes (ν(P═N): 1268 cm^{-1} (**11a**), 1275 cm^{-1} (**11b**)) additional bands tentatively attributed to the unreacted Pd(II) precursor and liberated PhCN (ν(C≡N) bands at 2122, 2226, and 2274 cm^{-1}, which only partially reduced in the intensity after rinsing with hexane and Et_2O), unidentified P(O)-products (ν(P═O) at 1221 cm^{-1}), and even the residual signals of the starting phosphine imides (P═N stretching vibrations at 1329 cm^{-1} (**5a**), 1296 cm^{-1} (**5b**)).

In the case of phosphine chalcogenide ligands **2** and **3**, the solid-phase cyclopalladation proceeded quantitatively upon heating of the homogenized mixtures with the Pd(II) precursor

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Organometallics XXXX, XXX, XXX–XXX

at the specified temperatures only for 5 min, which was confirmed by the IR and Raman spectroscopic data (Table 2, entries 3 and 4) (Figures S40−S52). The reaction temperatures were optimized in preliminary experiments upon heating in capillaries using a paper indicator for detection of HCl vapor liberation. The cyclopalladation of selenophosphoryl ligand **3** required slightly higher temperature than that of thiophosphoryl counterpart **2**. Whereas the sample of pincer complex **8** obtained under solvent-free conditions contained a considerable amount of benzonitrile, which can be removed by rinsing with hexane, thiophosphoryl-substituted analog **7** did not require any purification: the IR and Raman spectra of the resulting solid residue almost replicated those of an authentic sample obtained by the conventional solution-based method. Interestingly, even in the case of phosphoryl-functionalized ligand **4**, the formation of the corresponding pincer complex was observed under solvent-free conditions, although according to the data of ^{31}P NMR spectroscopy its yield was only 10% and did not increase upon prolonged heating (Table 2, entry 5). However, we emphasize that compared to the conventional solution-based method the suggested solid-phase approach provides the desired pincer complex **9** in a comparable yield only in 10 min of heating at 90 °C instead of 12 h of heating at 120 °C in benzonitrile (*vide supra*).

Preliminary Cytotoxicity Studies. Nowadays different types of transition metal complexes, including organometallic and coordination compounds of platinum, ruthenium, gold, titanium, and palladium, are extensively studied as potential anticancer drugs.[28] One of the recent trends in the development of Pd(II) cytotoxic agents is the use of pincer-type and related tridentate ligands,[14c,17a,b,29] which provide high thermodynamic and controlled kinetic stability along with the possibility to fine-tune the properties of complexes. The results of preliminary investigations on the cytotoxic activity of compounds **7**, **8**, **11b**, **11d**, and **12a-Cl** against several human cancer cell lines (human colon cancer HCT116, human breast cancer MCF7, and human prostate cancer PC3) as well as human embryonic kidney cells (HEK293) as a representative of normal cell lineages are summarized in Table 3. The ability to inhibit cell growth was estimated using the MTT assay. As can be seen, phosphine sulfide, phosphine selenide, and phosphonium ylide derivatives appeared to be only moderately active against the cancer lines explored (entries 1, 2, and 5). At the same time, their counterparts based on phosphine imide ligands exhibited considerable cytotoxic effects, with IC_{50} values falling in the low micromolar range (entries 3 and 4). Complex **11d** with an aliphatic substituent at the nitrogen atom of the P═N group appeared to be more active than its aryl-substituted analog **11b**. However, the latter demonstrated higher selectivity and was found to be less toxic toward normal cells than against HCT116 and PC3 cancer lineages. These results are in good agreement with the valuable cytotoxic properties of transition metal phosphine imide complexes recently reported by other research groups.[14c,30] Therefore, further investigations, including modification of phosphine imide ligand framework, seem to be promising.

Table 3. Cytotoxic Activity of the Hybrid Thiocarbamate Pd(II) Pincer Complexes Bearing Different Ancillary P(V)-Donor Groups

		cancer cell lines			normal cell line
entry	compound	HCT116	MCF7	PC3	HEK293
1	**7**	18 ± 3	48 ± 5	18 ± 4	20 ± 4
2	**8**	24 ± 4	42 ± 6	20 ± 4	31.5 ± 4.5
3	**11b**	7.5 ± 1.5	13 ± 3	8 ± 2	14.5 ± 1.5
4	**11d**	2.5 ± 0.5	4 ± 0.5	3 ± 1.5	4 ± 1
5	**12a-Cl**	46 ± 13	56 ± 11	52 ± 9	55 ± 13

CONCLUSIONS

To summarize the results presented, we have succeeded in the synthesis of a whole series of hybrid pincer ligands bearing different P(V)-ancillary donor groups: phosphine sulfide, phosphine selenide, phosphine oxide, phosphine imide, and phosphonium ylide. Most of the ligands derived readily underwent direct cyclopalladation under mild reaction conditions to afford the target pincer-type complexes in good yields, thus extending the application scope of organophosphorus(V) compounds in Pd(II) pincer chemistry. Even in the case of the phosphine oxide derivative, the proper choice of a thiocarbamate group as the second coordination arm allowed for the first synthesis of a platinum group metal pincer complex via direct cyclometalation of a phosphoryl-containing ligand. More importantly, in some cases the direct cyclopalladation was shown to proceed completely and selectively without recourse to the use of solvents even for purification. Preliminary data on cytotoxic activity of the resulting complexes revealed great potential of classical phosphine imide-based pincer complexes. We hope that the results presented will encourage wider use of pentavalent phosphorus compounds in pincer chemistry.

EXPERIMENTAL SECTION

General Remarks. Unless otherwise mentioned, all manipulations were carried out without taking precautions to exclude air and moisture. Dichloromethane was distilled over P_2O_5. Benzene and triethylamine were distilled over sodium. Tetrahydrofuran was distilled over sodium benzophenone ketyl. 3-(Diphenylphosphino)-phenol was synthesized starting from 3-bromoanisole by the reaction of its Grignard reagent with Ph_2PCl followed by sequential treatment of the resulting phosphine with HBr and NaOH.[18] Dimethylthiocarbamoyl chloride was obtained by the reaction of tetramethylthiuram disulfide with Cl_2;[31] since it gradually decomposes upon storage, it should be distilled prior to use. Phenyl[32] and 4-nitrophenyl[33] azides were obtained from the corresponding amines via diazotization under action of *in situ* generated nitrous acid followed by treatment of the resulting diazonium salts with NaN_3 according to the published procedures. Benzyl azide and *tert*-butyl azidoacetate were synthesized by the reactions of NaN_3 with benzyl bromide and *tert*-butyl bromoacetate, respectively.[34] ***Caution:*** *Azides are potentially explosive, and appropriate precautions must be taken when manipulating these compounds.* All other chemicals and solvents were used as purchased.

NMR spectra were recorded on Bruker Avance 400 and Avance 500 spectrometers, and the chemical shifts (δ) were referenced internally by the residual solvent signals relative to tetramethylsilane (^{1}H, ^{13}C) or externally to H_3PO_4 (^{31}P) or Me_2Se (^{77}Se). In most cases, ^{13}C{^{1}H} NMR spectra were registered using the *J*MODECHO mode; the signals for the *C* nuclei bearing odd and even numbers of protons have opposite polarities. The assignment of the NMR spectra of selenophosphoryl-functionalized ligand **3** and complex **8** was carried out based on the ^{1}H, ^{13}C{^{1}H}, ^{1}H−^{1}H−COSY, HMQC, and HMBC experiments. The results obtained were used for interpretation of the NMR spectra of the other compounds from this study.

The IR spectra were recorded on a Nicolet Magna-IR750 FT-spectrometer (resolution 2 cm^{-1}, 128 scans). The assignment of absorption bands in the IR spectra was made according to ref 35. Column chromatography was carried out using Macherey-Nagel silica gel 60 (MN Kieselgel 60, 70−230 mesh). Melting points were

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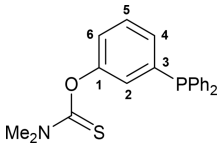
Organometallics XXXX, XXX, XXX−XXX

determined with an MPA 120 EZ-Melt automated melting point apparatus (Stanford Research Systems).

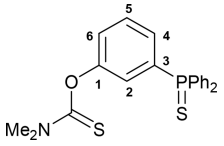
Syntheses. *O-[3-(Diphenylphosphinyl)phenyl] Dimethylthiocarbamate, **1**.*



A solution of 3-(diphenylphosphino)phenol (1.28 g, 4.60 mmol) in THF (7 mL) was added dropwise to a stirred suspension of NaH (used as a 60% dispersion in mineral oil; 0.24 g, 6.00 mmol) in THF (8 mL) at room temperature under an argon atmosphere. The resulting mixture was stirred at room temperature until evolution of hydrogen had ceased. Then, a solution of dimethylthiocarbamoyl chloride (0.74 g, 6.00 mmol) in THF (10 mL) was added dropwise. The reaction mixture was refluxed for 8 h. After cooling to room temperature, the mixture was diluted with benzene and washed with water. The aqueous fraction was separated and additionally extracted with benzene. The combined organic layer was dried over anhydrous Na_2SO_4 and evaporated under reduced pressure. The resulting residue was recrystallized from EtOAc−hexane (1:4) to give 1.08 g of **1** as a white crystalline solid. Yield: 64%. Mp: 108−110 °C. $^{31}P\{^1H\}$ NMR (161.98 MHz, C_6D_6): δ −5.30 ppm. ^1H NMR (400.13 MHz, C_6D_6): δ 2.49 and 2.96 (both s, 3H + 3H, NMe_2), 7.09−7.18 (m, 8H, H_{Ar}), 7.35−7.39 (m, 1H, H_{Ar}), 7.45 (d, 1H, H(C6), $^3J_{HH}$ = 6.8 Hz), 7.57−7.61 (m, 4H, H_{Ar}) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, C_6D_6): δ 37.41 and 42.43 (both s, NMe_2), 123.52 (s, C6), 128.25 (d, C5, $^3J_{CP}$ = 16.8 Hz), 128.69−128.84 (m, overlapping signals of *o*-C and *p*-C in PPh_2), 129.32 (d, C2, $^2J_{CP}$ = 8.0 Hz), 131.13 (d, C4, $^2J_{CP}$ = 22.4 Hz), 134.10 (d, *m*-C in PPh_2, $^3J_{CP}$ = 19.9 Hz), 137.34 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 12.1 Hz), 139.36 (d, C3, $^1J_{CP}$ = 13.9 Hz), 154.68 (d, C1, $^3J_{CP}$ = 6.8 Hz), 187.50 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 457(w), 496(w), 515(w), 551(w), 695(s), 712(w), 748(m), 800(w), 878(w), 998(w), 1024(w), 1067(w), 1095(w), 1124(s), 1179(w), 1206(s), 1265(w), 1288(m), 1399(m), 1411(m), 1431(m), 1471(m), 1540(br, s) (νNC(S)O), 1582(w), 1593(w), 2934(w), 3053(w). Anal. Calcd for $C_{21}H_{20}NOPS$: C, 69.02; H, 5.52; N, 3.83. Found: C, 68.97; H, 5.51; N, 3.73%.

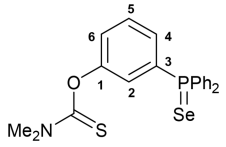
General Procedure for the Synthesis of Phosphine Chalcogenide Ligands 2 and 3. A stirred solution of phosphine **1** (0.52 g, 1.42 mmol) and elemental sulfur or selenium (1.42 mmol) in benzene (25 mL) was refluxed for 3 h. After cooling to room temperature, the resulting mixture was purified by column chromatography on silica gel (eluent CH_2Cl_2−petroleum ether (1:1)) to give ligands **2** and **3** as white (**2**) or light-pink (**3**) crystalline solids.

*O-[3-(Diphenylthiophosphoryl)phenyl] Dimethylthiocarbamate, **2**.*



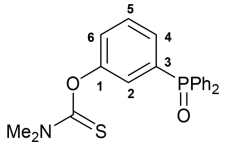
Yield: 0.48 g (85%). Mp: 140−141 °C. $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 42.92 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.31 and 3.43 (both s, 3H + 3H, NMe_2), 7.24 (d, 1H, H(C6), $^3J_{HH}$ = 7.9 Hz), 7.44−7.54 (m, 8H, H_{Ar}), 7.61 (dd, 1H, H(C4), $^3J_{HP}$ = 12.8 Hz, $^3J_{HH}$ = 7.8 Hz), 7.77 (dd, 4H, *o*-H in $P(S)Ph_2$, $^3J_{HP}$ = 13.4 Hz, $^3J_{HH}$ = 7.5 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 38.84 and 43.33 (both s, NMe_2), 126.11 (d, C6, $^4J_{CP}$ = 2.5 Hz), 127.02 (d, C5, $^3J_{CP}$ = 11.4 Hz), 128.63 (d, *m*-C in $P(S)Ph_2$, $^3J_{CP}$ = 12.6 Hz), 129.43 (d, C4, $^2J_{CP}$ = 14.1 Hz), 129.53 (d, C2, $^2J_{CP}$ = 10.3 Hz), 131.70 (d, *p*-C in $P(S)Ph_2$, $^4J_{CP}$ = 2.9 Hz), 132.35 (d, *o*-C in $P(S)Ph_2$, $^2J_{CP}$ = 10.9 Hz), 132.55 (d, *ipso*-C in $P(S)Ph_2$, $^1J_{CP}$ = 85.7 Hz), 134.18 (d, C3, $^1J_{CP}$ = 84.6 Hz), 153.87 (d, C1, $^3J_{CP}$ = 16.6 Hz), 187.24 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 449(w), 512(m), 522(m), 613(w), 636(w), 648(m) (νP═S), 691(m), 717(s), 745(w), 764(w), 804(w), 878(w), 998(w), 1025(w), 1068(w), 1100(s), 1128(s), 1157(w), 1209(s), 1267(w), 1284(m), 1309(w), 1392(m), 1409(m), 1437(m), 1471(m), 1478(w), 1540(br, m) (νNC(S)O), 1577(w), 2936(w), 3057(w). Raman (solid, $\Delta\nu$/cm^{-1}): 175(vw), 209(vw), 237(m), 251(m), 271(w), 304(vw), 347(m), 447(vw), 520(vw), 542(m), 612(w), 635(m), 650(w) (νP═S), 670(vw), 695(vw), 721(vw), 803(vw), 877(vw), 959(vw), 997(s), 1025(m), 1069(vw), 1095(m), 1127(vw), 1156(vw), 1184(vw), 1208(vw), 1285(vw), 1409(vw), 1445(vw), 1584(w), 2938(vw), 3062(m). Anal. Calcd for $C_{21}H_{20}NOPS_2$: C, 63.45; H, 5.07; N, 3.52. Found: C, 63.43; H, 5.01; N, 3.43%.

*O-[3-(Diphenylselenophosphoryl)phenyl] Dimethylthiocarbamate, **3**.*



Yield: 0.33 g (52%). Mp: 130−132 °C. $^{77}Se\{^1H\}$ NMR (95.38 MHz, $CDCl_3$): δ −266.89 (d, $^1J_{SeP}$ = 734.0 Hz) ppm. $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 34.88 ($^1J_{PSe}$ = 734.0 Hz) ppm. ^1H NMR (500.13 MHz, $CDCl_3$): δ 3.32 and 3.43 (both s, 3H + 3H, NMe_2), 7.22 (d, 1H, H(C6), $^3J_{HH}$ = 7.8 Hz), 7.46−7.52 (m, 8H, H_{Ar}), 7.59 (dd, 1H, H(C4), $^3J_{HP}$ = 13.0 Hz, $^3J_{HH}$ = 7.7 Hz), 7.78 (dd, 4H, *o*-H in $P(Se)Ph_2$, $^3J_{HP}$ = 13.6 Hz, $^3J_{HH}$ = 7.5 Hz) ppm. $^{13}C\{^1H\}$ NMR (125.76 MHz, $CDCl_3$): δ 38.84 and 43.33 (both s, NMe_2), 126.13 (d, C6, $^4J_{CP}$ = 2.4 Hz), 127.40 (d, C5, $^3J_{CP}$ = 11.5 Hz), 128.64 (d, *m*-C in $P(Se)Ph_2$, $^3J_{CP}$ = 12.7 Hz), 129.40 (d, C4, $^2J_{CP}$ = 14.4 Hz), 129.94 (d, C2, $^2J_{CP}$ = 10.7 Hz), 131.41 (d, *ipso*-C in $P(Se)Ph_2$, $^1J_{CP}$ = 75.4 Hz), 131.73 (d, *p*-C in $P(Se)Ph_2$, $^4J_{CP}$ = 3.2 Hz), 132.76 (d, *o*-C in $P(Se)Ph_2$, $^2J_{CP}$ = 11.0 Hz), 133.08 (d, C3, $^1J_{CP}$ = 68.4 Hz), 153.83 (d, C1, $^3J_{CP}$ = 16.4 Hz), 187.23 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 448(vw), 488(w), 507(m), 517(m), 533(w), 571(s) (νP═Se), 619(vw), 640(vw), 690(s), 699(s), 714(m), 744(m), 763(w), 802(w), 878(vw), 997(w), 1025(w), 1068(w), 1095(s), 1126(s), 1169(w), 1209(s), 1266(w), 1284(m), 1309(w), 1392(m), 1408(m), 1436(m), 1477(m), 1540(br, m) (νNC(S)O), 1577(w), 2935(w), 3054(w). Raman (solid, $\Delta\nu$/cm^{-1}): 173(w), 206(w), 246(m), 277(w), 339(w), 445(vw), 485(vw), 530(m), 568(m) (νP═Se), 613(w), 640(vw), 668(w), 694(w), 713(w), 798(w), 877(vw), 928(vw), 997(s), 1024(m), 1068(w), 1091(m), 1126(vw), 1156(w), 1180(w), 1208(w), 1283(vw), 1391(vw), 1408(vw), 1433(vw), 1476(vw), 1583(m), 2939(vw), 2986(vw), 3002(vw), 3055(m).

*O-[3-(Diphenylphosphoryl)phenyl] Dimethylthiocarbamate, **4**.*



A mixture of phosphine **1** (220 mg, 0.602 mmol), 33% aqueous H_2O_2 (62 mg, 0.602 mmol), chloroform (4 mL), and water (1 mL) was stirred at room temperature for 3 h. The resulting mixture was diluted with chloroform and twice washed with water. The organic layer was separated, dried over anhydrous Na_2SO_4, and evaporated under reduced pressure. The residue obtained was purified by column chromatography on silica gel (eluent $CHCl_3$ and $CHCl_3$−EtOH (100:1)) to give 172 mg of ligand **4** as a white crystalline solid. Yield: 75%. Mp: 171−173 °C. $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 28.48 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.32 and 3.44 (both s, 3H + 3H, NMe_2), 7.26−7.28 (m, 1H, H(C6)), 7.36 (d, 1H, H(C2), $^3J_{HP}$ = 12.5 Hz), 7.46−7.63 (m, 8H, H_{Ar}), 7.71 (dd, 4H, *o*-H in $P(O)Ph_2$, $^3J_{HP}$ = 11.6 Hz, $^3J_{HH}$ = 7.9 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 38.79 and 43.29 (both s, NMe_2), 126.44 (d, C6, $^4J_{CP}$ = 2.0 Hz), 126.73 (d, C5, $^3J_{CP}$ = 10.6 Hz), 128.59 (d, *m*-C in $P(O)Ph_2$, $^3J_{CP}$ = 12.2 Hz), 129.37 (d, C2, $^2J_{CP}$ = 9.2 Hz), 129.54 (d, C4, $^2J_{CP}$ = 13.6 Hz), 132.07 (d, *p*-C in $P(O)Ph_2$, $^4J_{CP}$ = 2.2 Hz), 132.16 (d, *ipso*-C in $P(O)Ph_2$, $^1J_{CP}$ = 104.9 Hz), 132.17 (d, *o*-C in $P(O)Ph_2$, $^2J_{CP}$ = 10.1 Hz), 133.77 (d, C3, $^1J_{CP}$ = 102.9 Hz), 153.83

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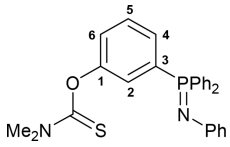
Organometallics XXXX, XXX, XXX−XXX

(d, C1, $^3J_{CP}$ = 15.7 Hz), 187.24 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 477(w), 532(m), 542(s), 559(m), 696(m), 724(s), 755(w), 762(w), 812(w), 998(w), 1026(vw), 1068(w), 1079(w), 1108(m), 1122(s), 1130(m), 1189(s) (νP═O), 1213(s), 1267(w), 1289(m), 1309(w), 1396(m), 1410(m), 1434(m), 1475(m), 1540(br, m) (νNC(S)O), 1578(w), 1589(w), 2873(vw), 2940(w), 2984(w), 3034(w), 3062(w). Anal. Calcd for $C_{21}H_{20}NO_2PS$: C, 66.13; H, 5.29; N, 3.67. Found: C, 66.07; H, 5.36; N, 3.58%.

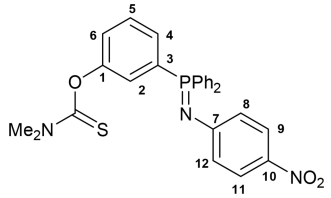
General Procedure for the Synthesis of Phosphine Imide Ligands 5a,b. A stirred solution of phosphine **1** (150 mg, 0.410 mmol) and the corresponding aryl azide (0.410 mmol) in benzene (7 mL) was refluxed for 1 h (in the case of 4-nitrophenyl azide) or 2 h (in the case of phenyl azide) under an argon atmosphere. After cooling to room temperature, the reaction mixture was evaporated to dryness. The resulting residue was kept under vacuum (in the case of **5b**) or recrystallized from C_6H_6−hexane (1:3) (in the case of **5a**) to give the target ligands as white (**5a**) or bright-yellow (**5b**) crystalline solids.

O-[3-(N,P,P-Triphenylphosphorimidoyl)phenyl] Dimethylthiocarbamate, ***5a****.*



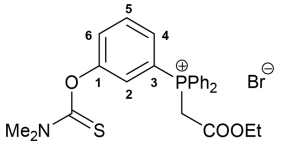
Yield: 158 mg (84%). Mp: 140−143 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, C_6D_6): δ −1.20 ppm. ^1H NMR (400.13 MHz, C_6D_6): δ 2.45 and 2.93 (both s, 3H + 3H, NMe_2), 6.93 (t, 1H, *p*-H in NPh, $^3J_{HH}$ = 7.2 Hz), 7.05−7.10 (m, 8H, H_{Ar}), 7.27−7.33 (m, 2H, H_{Ar}), 7.41 (d, 2H, *o*-H in NPh, $^3J_{HH}$ = 8.1 Hz), 7.82 (dd, 1H, H(C4), $^3J_{HP}$ = 11.6 Hz, $^3J_{HH}$ = 7.0 Hz), 7.93 (d, 1H, H(C2), $^3J_{HP}$ = 12.4 Hz), 8.00−8.06 (m, 4H, H_{Ar}) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, C_6D_6): δ 37.34 and 42.32 (both s, NMe_2), 117.60 (s, *p*-C in NPh), 123.73 (d, *o*-C in NPh, $^3J_{CP}$ = 17.8 Hz), 125.94 (d, C6, $^4J_{CP}$ = 2.2 Hz), 128.42 (d, *m*-C in PPh_2, $^3J_{CP}$ = 11.9 Hz), 128.92 (s, *m*-C in NPh), 129.41 (d, C4, $^2J_{CP}$ = 13.4 Hz), 129.79 (d, C2, $^2J_{CP}$ = 9.2 Hz), 131.28 (d, *p*-C in PPh_2, $^4J_{CP}$ = 1.9 Hz), 131.57 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 99.9 Hz), 132.63 (d, *o*-C in PPh_2, $^2J_{CP}$ = 9.6 Hz), 133.26 (d, C3, $^1J_{CP}$ = 96.9 Hz), 151.57 (s, *ipso*-C in NPh), 154.09 (d, C1, $^3J_{CP}$ = 15.4 Hz), 187.00 (s, C═S) ppm (the signal of C5 carbon nucleus was not assigned due to overlapping with the solvent signal). IR (KBr, ν/cm^{-1}): 516(w), 528(m), 576(w), 695(m), 717(m), 753(m), 799(w), 877(w), 998(w), 1018(w), 1043(w), 1071(w), 1108(m), 1125(m), 1170(w), 1204(s), 1267(w), 1285(m), 1330(s) (νP═N), 1397(m), 1436(m), 1484(s), 1539(br, m) (νNC(S)O), 1590(s), 2937(vw), 3022(w), 3054(w), 3069(w). Anal. Calcd for $C_{27}H_{25}N_2OPS$: C, 71.03; H, 5.52; N, 6.14. Found: C, 71.07; H, 5.59; N, 6.04%.

O-{3-[P,P-Diphenyl-N-(4-nitrophenyl)phosphorimidoyl]phenyl} Dimethylthiocarbamate, ***5b****.*



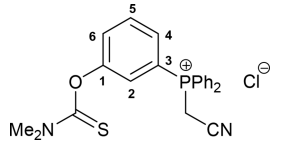
Yield: 205 mg (quant.). Mp: 78−80 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, C_6D_6): δ 4.50 ppm. ^1H NMR (400.13 MHz, C_6D_6): δ 2.47 and 2.90 (both s, 3H + 3H, NMe_2), 6.89 (d, 2H, H_{Ar}, $^3J_{HH}$ = 8.9 Hz), 7.03−7.11 (m, 8H, H_{Ar}), 7.56 (dd, 1H, H(C4), $^3J_{HP}$ = 11.8 Hz, $^3J_{HH}$ = 6.9 Hz), 7.77−7.82 (m, 5H, H_{Ar}), 8.08 (d, 2H, H_{Ar}, $^3J_{HH}$ = 8.9 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, C_6D_6): δ 37.49 and 42.46 (both s, NMe_2), 122.43 (d, C8 and C12, $^3J_{CP}$ = 19.1 Hz), 125.54 (d, C9 and C11, $^4J_{CP}$ = 1.1 Hz), 126.76 (d, C6, $^4J_{CP}$ = 2.3 Hz), 128.82 (d, *m*-C in PPh_2, $^3J_{CP}$ = 12.3 Hz), 129.56 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 101.1 Hz), 129.61 (d, C2, $^2J_{CP}$ = 9.4 Hz), 129.85 (d, C4, $^2J_{CP}$ = 13.8 Hz), 131.06 (d, C3, $^1J_{CP}$ = 98.2 Hz), 132.09 (d, *p*-C in PPh_2, $^4J_{CP}$ = 2.6 Hz), 132.55 (d, *o*-C in PPh_2, $^2J_{CP}$ = 10.0 Hz), 138.94 (s, C10), 154.37 (d, C1, $^3J_{CP}$ = 16.1 Hz), 159.38 (s, C7), 186.89 (s, C═S) ppm (the signal of C5 carbon nucleus was not assigned due to overlapping with the solvent signal). IR (KBr, ν/cm^{-1}): 528(w), 557(w), 608(vw), 694(w), 720(w), 756(w), 844(w), 996(w), 1016(w), 1106(m), 1175(w), 1208(m), 1299(br, s) (νP═N), 1370(br, w), 1396(w), 1437(w), 1490(m), 1540(br, w) (νNC(S)O), 1584(m), 2854(vw), 2928(vw), 3056(vw). Raman (solid, $\Delta\nu$/cm^{-1}): 257(w), 321(vw), 422(vw), 561(w), 609(w), 638(vw), 721(vw), 763(w), 855(m), 998(m), 1017(w), 1075(w), 1107(m), 1176(w), 1209(w), 1298(br, s) (νP═N), 1396(vw), 1459(vw), 1514(vw), 1585(m), 3063(w). Anal. Calcd for $C_{27}H_{24}N_3O_3PS$: C, 64.66; H, 4.82; N, 8.38. Found: C, 64.81; H, 4.87; N, 8.31%.

{3-[(Dimethylthiocarbamoyl)oxy]phenyl}(2-ethoxy-2-oxoethyl)-diphenylphosphonium Bromide, ***6a****.*



A stirred solution of phosphine **1** (302 mg, 0.826 mmol) and ethyl bromoacetate (138 mg, 0.826 mmol) in benzene (8 mL) was refluxed for 5 h. After cooling to room temperature, the resulting precipitate was collected by filtration, rinsed with benzene and Et_2O and dried in *vacuo* to give 389 mg of compound **6a** as a white crystalline solid. Yield: 88%. Mp: >137 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 20.66 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 1.09 (t, 3H, $COOCH_2C\underline{H}_3$, $^3J_{HH}$ = 7.1 Hz), 3.38 and 3.43 (both s, 3H + 3H, NMe_2), 4.06 (q, 2H, $COOC\underline{H}_2CH_3$, $^3J_{HH}$ = 7.1 Hz), 5.59 (d, 2H, CH_2P, $^2J_{HP}$ = 13.1 Hz), 7.46 (d, 1H, H(C6), $^3J_{HH}$ = 7.8 Hz), 7.63 (d, 1H, H(C2), $^3J_{HP}$ = 14.1 Hz), 7.66−7.72 (m, 5H, H_{Ar}), 7.76−7.81 (m, 3H, H_{Ar}), 7.97 (dd, 4H, *o*-H in PPh_2, $^3J_{HP}$ = 13.4 Hz, $^3J_{HH}$ = 7.8 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 13.48 (s, $COOCH_2\underline{C}H_3$), 32.89 (d, CH_2P, $^1J_{CP}$ = 56.1 Hz), 38.96 and 43.18 (both s, NMe_2), 62.69 (s, $COO\underline{C}H_2CH_3$), 117.31 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 89.2 Hz), 118.30 (d, C3, $^1J_{CP}$ = 89.7 Hz), 128.70 (d, C5, $^3J_{CP}$ = 11.4 Hz), 129.36 (d, C6, $^4J_{CP}$ = 2.6 Hz), 130.05 (d, *m*-C in PPh_2, $^3J_{CP}$ = 13.3 Hz), 131.05 (d, C2, $^2J_{CP}$ = 10.2 Hz), 131.16 (d, C4, $^2J_{CP}$ = 15.1 Hz), 133.82 (d, *o*-C in PPh_2, $^2J_{CP}$ = 10.9 Hz), 135.01 (d, *p*-C in PPh_2, $^4J_{CP}$ = 2.9 Hz), 154.21 (d, C1, $^3J_{CP}$ = 17.6 Hz), 163.97 (d, $\underline{C}OOCH_2CH_3$, $^2J_{CP}$ = 3.6 Hz), 186.14 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 467(w), 510(w), 520(w), 547(vw), 690(m), 719(w), 737(w), 751(w), 789(w), 857(w), 873(vw), 996(w), 1021(w), 1110(s), 1153(m), 1167(m), 1215(s), 1287(m), 1312(m), 1367(w), 1397(m), 1414(w), 1437(m), 1478(w), 1542(br, m) (νNC(S)O), 1586(w), 1721(s) (νC═O), 2734(w), 2798(w), 2850(w), 2984(w), 3005(w), 3050(w). Anal. Calcd for $C_{25}H_{27}BrNO_3PS$: C, 56.40; H, 5.11; N, 2.63. Found: C, 56.62; H, 5.25; N, 2.61%.

(Cyanomethyl){3-[(dimethylthiocarbamoyl)oxy]phenyl}-diphenylphosphonium Chloride, ***6b****.*



A stirred mixture of phosphine **1** (105 mg, 0.287 mmol) and chloroacetonitrile (3 mL) was heated at 90 °C for 3 h. After cooling to room temperature, the excess of $ClCH_2CN$ was removed in *vacuo*. The resulting residue was crystallized upon addition of Et_2O and recrystallized from EtOH−EtOAc (1:6) to give 90 mg of compound **6b** as a white crystalline solid. Yield: 71%. Mp: >155 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 21.77 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.37 and 3.42 (both s, 3H + 3H, NMe_2), 6.67 (d, 2H, CH_2P, $^2J_{HP}$ = 15.6 Hz), 7.51 (d, 1H, H(C6), $^3J_{HH}$ = 7.8 Hz), 7.62 (d, 1H, H(C2), $^3J_{HP}$ = 14.0 Hz), 7.71−7.89 (m, 7H, H_{Ar}), 7.94 (dd, 1H, H(C4), $^3J_{HP}$ = 12.9 Hz, $^3J_{HH}$ = 7.9 Hz), 8.10 (dd, 4H, *o*-H in PPh_2, $^3J_{HP}$ = 13.4 Hz, $^3J_{HH}$ 7.7 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 16.58 (d, CH_2P, $^1J_{CP}$ = 54.6 Hz), 39.19 and 43.45 (both s, NMe_2), 112.39 (d, CN, $^2J_{CP}$ = 9.5 Hz), 116.21 (d, *ipso*-C in

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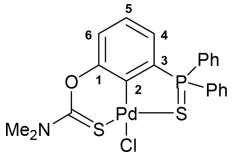
Organometallics XXXX, XXX, XXX−XXX

PPh_2, $^1J_{CP}$ = 89.1 Hz), 117.30 (d, C3, $^1J_{CP}$ = 89.6 Hz), 129.17 (d, C5, $^3J_{CP}$ = 11.7 Hz), 130.26 (d, C6, $^4J_{CP}$ = 1.9 Hz), 130.59 (d, *m*-C in PPh_2, $^3J_{CP}$ = 13.5 Hz), 131.67 (d, C2, $^2J_{CP}$ = 10.3 Hz), 131.74 (d, C4, $^2J_{CP}$ = 15.7 Hz), 134.44 (d, *o*-C in PPh_2, $^2J_{CP}$ = 11.0 Hz), 135.82 (d, *p*-C in PPh_2, $^4J_{CP}$ = 2.7 Hz), 154.63 (d, C1, $^3J_{CP}$ = 18.2 Hz), 186.57 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 451(w), 497(m), 543(w), 556(m), 688(m), 723(m), 746(m), 770(w), 802(w), 866(vw), 996(w), 1114(s), 1177(w), 1215(s), 1287(m), 1401(m), 1439(m), 1482(w), 1546(br, m) (νNC(S)O), 1587(w), 2250(w) (νC≡N), 2495(vw), 2692(w), 2786(w), 2990(w), 3059(vw). Anal. Calcd for $C_{23}H_{22}ClN_2OPS$: C, 62.65; H, 5.03; N, 6.35. Found: C, 62.54; H, 4.85; N, 6.36%.

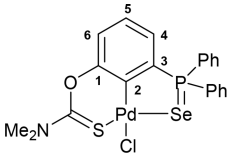
General Procedure for the Synthesis of Pincer Complexes 7 and 8. A solution of $PdCl_2(NCPh)_2$ (61 mg, 0.159 mmol) in CH_2Cl_2 (4 mL) was added dropwise to a solution of the corresponding ligand (0.159 mmol) in CH_2Cl_2 (4 mL). The dark-red reaction mixture was left under ambient conditions for 1 day. The resulting yellow solution was purified by column chromatography (eluent: $CHCl_3$–EtOH (50:1) (**7**) or CH_2Cl_2–EtOH (50:1) (**8**)) to give complexes **7**, **8** as yellow crystalline solids.

*Complex [κ³-S,N,S-(L)Pd(II)Cl], **7**.*



Yield: 73 mg (85%). Mp: >250 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 48.50 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.41 and 3.49 (both s, 3H + 3H, NMe_2), 6.85 (ddd, 1H, H(C4), $^3J_{HP}$ = 10.8 Hz, $^3J_{HH}$ = 7.0 Hz, $^4J_{HH}$ = 1.3 Hz), 7.03–7.12 (m, 2H, H_{Ar}), 7.52–7.57 (m, 4H, H_{Ar}), 7.62–7.66 (m, 2H, H_{Ar}), 7.81 (ddd, 4H, *o*-H in $P(S)Ph_2$, $^3J_{HP}$ = 13.5 Hz, $^3J_{HH}$ = 7.8 Hz, $^4J_{HH}$ = 1.3 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 39.64 and 43.11 (both s, NMe_2), 120.55 (s, C6), 125.06 (d, C5, $^3J_{CP}$ = 15.3 Hz), 128.69 (d, C4, $^2J_{CP}$ = 18.5 Hz), 128.85 (d, *m*-C in $P(S)Ph_2$, $^3J_{CP}$ = 12.7 Hz), 129.67 (d, *ipso*-C in $P(S)Ph_2$, $^1J_{CP}$ = 80.5 Hz), 132.35 (d, *o*-C in $P(S)Ph_2$, $^2J_{CP}$ = 11.0 Hz), 132.65 (d, *p*-C in $P(S)Ph_2$, $^4J_{CP}$ = 2.6 Hz), 140.09 (d, C2, $^2J_{CP}$ = 24.9 Hz), 149.06 (d, C3, $^1J_{CP}$ = 106.6 Hz), 153.01 (d, C1, $^3J_{CP}$ = 21.8 Hz), 177.17 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 483(w), 502(w), 516(m), 554(w), 608(m) and 625(m) (both νP═S), 690(s), 708(s), 719(m), 737(s), 752(w), 785(w), 873(w), 997(w), 1026(w), 1104(s), 1153(m), 1183(w), 1237(s), 1276(m), 1295(s), 1404(s), 1436(s), 1481(w), 1555(br, s) (νNC(S)O), 1574(m), 2925(w), 3045(w). Raman (solid, $\Delta\nu$/cm^{-1}): 184(w), 207(m), 234(w), 257(w), 283(w), 330(w), 363(s), 393(w), 459(w), 483(w), 524(m), 552(w), 605(m) and 623(w) (both νP═S), 639(w), 738(w), 789(vw), 875(vw), 909(vw), 927(vw), 955(w), 996(s), 1024(m), 1076(vw), 1101(m), 1158(w), 1233(vw), 1276(w), 1399(w), 1434(w), 1451(w), 1477(vw), 1509(vw), 1551(w), 1584(m), 2865(vw), 2925(w), 2955(vw), 3003(vw), 3049(w). Anal. Calcd for $C_{21}H_{19}ClNOPPdS_2$: C, 46.85; H, 3.56; N, 2.60. Found: C, 46.49; H, 3.44; N, 2.47%.

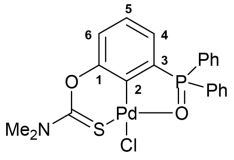
*Complex [κ³-Se,N,S-(L)Pd(II)Cl], **8**.*



Yield: 72 mg (77%). Mp: >220 °C (dec.). $^{77}Se\{^1H\}$ NMR (95.38 MHz, $CDCl_3$): δ −10.09 (d, $^1J_{SeP}$ = 527.3 Hz) ppm. $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 30.24 ($^1J_{PSe}$ = 527.3 Hz) ppm. ^1H NMR (500.13 MHz, $CDCl_3$): δ 3.41 and 3.48 (both s, 3H + 3H, NMe_2), 6.74 (ddd, H(C4), $^3J_{HP}$ = 10.9 Hz, $^3J_{HH}$ = 7.1 Hz, $^4J_{HH}$ = 1.6 Hz), 7.02–7.08 (m, 2H, H_{Ar}), 7.51–7.55 (m, 4H, H_{Ar}), 7.60–7.64 (m, 2H, H_{Ar}), 7.78 (ddd, 4H, *o*-H in $P(Se)Ph_2$, $^3J_{HP}$ = 13.8 Hz, $^3J_{HH}$ = 7.8 Hz, $^4J_{HH}$ = 1.3 Hz) ppm. $^{13}C\{^1H\}$ NMR (125.76 MHz, $CDCl_3$): δ 39.75 and 43.47 (both s, NMe_2), 120.65 (d, C6, $^4J_{CP}$ = 3.1 Hz), 125.09 (d, C5, $^3J_{CP}$ = 14.9 Hz), 129.16 (d, *ipso*-C in $P(Se)Ph_2$, $^1J_{CP}$ = 72.9 Hz), 129.17 (d, *m*-C in $P(Se)Ph_2$, $^3J_{CP}$ = 12.7 Hz), 129.63 (d, C4, $^2J_{CP}$ = 14.6 Hz), 132.91 (d, *p*-C in $P(Se)Ph_2$, $^4J_{CP}$ = 2.8 Hz), 132.95 (d, *o*-C in $P(Se)Ph_2$, $^2J_{CP}$ = 11.1 Hz), 141.32 (d, C2, $^2J_{CP}$ = 27.9 Hz), 149.60 (d, C3, $^1J_{CP}$ = 99.8 Hz), 153.89 (d, C1, $^3J_{CP}$ = 23.3 Hz), 178.73 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 440(vw), 473(w), 515(s), 536(w), 566(m) (νP═Se), 617(vw), 692(s), 700(m), 717(m), 736(s), 761(w), 784(w), 870(vw), 996(w), 1100(m), 1138(m), 1160(m), 1234(s), 1268(m), 1290(s), 1396(s), 1406(s), 1437(s), 1480(w), 1557(br, s) (νNC(S)O), 1574(m), 2926(vw), 2965(vw), 3043(vw). Raman (solid, $\Delta\nu$/cm^{-1}): 173(m), 193(w), 225(w), 237(w), 272(m), 337(m), 393(w), 454(w), 472(vw), 506(vw), 525(w), 533(w), 564(w) (νP═Se), 616(w), 702(w), 734(w), 954(w), 998(s), 1023(m), 1073(vw), 1098(m), 1137(w), 1161(w), 1183(w), 1235(vw), 1265(vw), 1290(vw), 1407(w), 1436(vw), 1551(w), 1573(w), 1584(m), 2871(vw), 2930(w), 2967(w), 3006(vw), 3048(m).

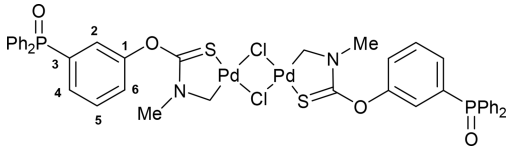
Cyclopalladation of Phosphine Oxide Ligand 4. A stirred solution of ligand **4** (57 mg, 0.149 mmol) and $PdCl_2(NCPh)_2$ (57 mg, 0.149 mmol) in benzonitrile (2.5 mL) was heated at 110 °C for 12 h. After cooling to room temperature, the reaction mixture was poured into hexane (50 mL). The resulting precipitate was collected by filtration and purified by column chromatography on silica gel (gradient elution with neat $CHCl_3$ and $CHCl_3$–EtOH mixture (from 500:1 to 50:1)) to give complexes **9** and **10** as yellow crystalline solids.

*Complex [κ³-S,N,O-(L)Pd(II)Cl], **9**.*



Yield: 11 mg (14%). Mp: >200 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 61.49 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.41 and 3.50 (both s, 3H + 3H, NMe_2), 7.03 (ddd, 1H, H(C4), $^3J_{HP}$ = 10.0 Hz, $^3J_{HH}$ = 7.3 Hz, $^4J_{HH}$ = 0.7 Hz), 7.07 (d, 1H, H(C6), $^3J_{HH}$ = 8.0 Hz), 7.17–7.22 (m, 1H, H(C5)), 7.52–7.56 (m, 4H, H_{Ar}), 7.63–7.67 (m, 2H, H_{Ar}), 7.84 (ddd, 4H, *o*-H in $P(O)Ph_2$, $^3J_{HP}$ = 12.3 Hz, $^3J_{HH}$ = 7.6 Hz, $^4J_{HH}$ = 0.8 Hz) ppm. IR (KBr, ν/cm^{-1}): 473(w), 515(w), 559(s), 693(m), 728(s), 743(s), 790(w), 875(vw), 997(vw), 1026(vw), 1060(s), 1126(s) (νP═O), 1159(w), 1194(vw), 1248(m), 1276(m), 1301(s), 1404(m), 1437(m), 1484(vw), 1556(br, s) (νNC(S)O), 1577(w), 2855(vw), 2921(vw), 2955(vw), 3032(w), 3052(w).

*Complex [κ²-C,S-(L)Pd(II)Cl]₂, **10**.*



Yield: 27 mg (35%). Mp: >180 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 27.98 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.14 (s, 6H, NMe), 3.82 (s, 4H, NCH_2Pd), 7.33 (d, 2H, H(C6), $^3J_{HH}$ = 8.0 Hz), 7.38 (d, 2H, H(C2), $^3J_{HP}$ = 12.6 Hz), 7.45–7.59 (m, 16H, H_{Ar}), 7.70 (dd, 8H, *o*-H in $P(O)Ph_2$, $^3J_{HP}$ = 11.6 Hz, $^3J_{HH}$ = 7.7 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 40.13 (s, NMe), 41.39 (s, NCH_2Pd), 125.47 (d, C6, $^4J_{CP}$ = 3.2 Hz), 125.54 (d, C5, $^3J_{CP}$ = 11.3 Hz), 128.80 (d, *m*-C in $P(O)Ph_2$, $^3J_{CP}$ = 12.2 Hz), 130.30 (d, C4, $^2J_{CP}$ = 13.2 Hz), 131.05 (d, C2, $^2J_{CP}$ = 9.1 Hz), 131.59 (d, *ipso*-C in $P(O)Ph_2$, $^1J_{CP}$ = 111.9 Hz), 132.10 (d, *o*-C in $P(O)Ph_2$, $^2J_{CP}$ = 10.1

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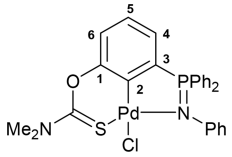
Organometallics XXXX, XXX, XXX–XXX

Hz), 132.36 (d, *p*-C in P(O)Ph_2, $^4J_{CP}$ = 2.4 Hz), 135.30 (d, C3, $^1J_{CP}$ = 101.5 Hz), 151.74 (d, C1, $^3J_{CP}$ = 16.1 Hz), 185.12 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 484(w), 541(s), 668(w), 694(m), 724(s), 752(w), 800(vw), 883(w), 972(vw), 998(w), 1028(vw), 1072(w), 1110(sh, m), 1119(m), 1194(m) (νP═O), 1225(s), 1265(s), 1309(vw), 1416(m), 1437(m), 1474(w), 1575(m), 1616(m), 2881(vw), 2928(vw), 3054(w). Raman (solid, $\Delta\nu$/cm^{-1}): 179(w), 213(m), 252(m), 287(m), 350(w), 412(w), 495(w), 546(vw), 616(w), 628(vw), 661(m), 692(m), 727(vw), 798(vw), 997(s), 1026(m), 1074(vw), 1121(w), 1162(w), 1195(m) (νP═O), 1232(vw), 1574(w), 1591(m), 2882(vw), 2931(w), 3056(m). Anal. Calcd for $C_{42}H_{38}Cl_2N_2O_4P_2Pd_2S_2$: C, 48.29; H, 3.67; N, 2.68. Found: C, 48.14; H, 3.59; N, 2.67%.

General Procedure for the Synthesis of Complexes 11a,b (Method A). A solution of $PdCl_2(NCPh)_2$ (44 mg, 0.115 mmol) in dichloromethane (2 mL) was added dropwise to a solution of preformed ligand **5a** or **5b** (0.115 mmol) and Et_3N (16 μL, 0.115 mmol) in benzene (4 mL) under an argon atmosphere. The reaction mixture was left under ambient conditions for 1 day and evaporated to dryness. The resulting residue was purified by column chromatography on silica gel (elution with $CHCl_3$−EtOH (20:1) in the case of complex **11a** or gradient elution with neat $CHCl_3$ and $CHCl_3$−EtOH mixture (from 1000:1 to 100:1) in the case of complex **11b**) to give the target complexes as yellow crystalline solids.

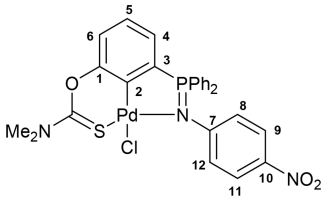
General Procedure for the Synthesis of Complexes 11a−d (Method B). A stirred solution of phosphine **1** (102 mg, 0.279 mmol) and the corresponding azide (0.279 mmol) in benzene (3 mL) was refluxed for 2 h under an argon atmosphere. After cooling to room temperature, a solution of Et_3N (39 μL, 0.279 mmol) in benzene (1 mL) was added to the reaction mixture. Then, a solution of $PdCl_2(NCPh)_2$ (107 mg, 0.279 mmol) in dichloromethane (2 mL) was added dropwise. The reaction mixture was left under ambient conditions for 3 days and evaporated to dryness. The resulting residue was purified by column chromatography on silica gel (elution with $CHCl_3$−EtOH (20:1) in the case of complex **11a** or gradient elution with neat $CHCl_3$ and $CHCl_3$−EtOH mixture (from 1000:1 to 50:1) in the other cases) to afford the target complexes as yellow (**11a**,**b**) or light-yellow (**11c**,**d**) crystalline solids.

Complex [κ^3-S,C,N-(L)Pd(II)Cl], ***11a****.*



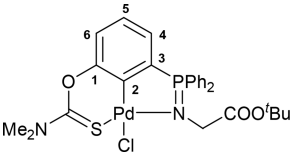
Yield: 57 mg (83%) (method A); 155 mg (93%) (method B). Mp: >233 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 41.44 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.35 and 3.42 (both s, 3H + 3H, NMe_2), 6.76 (t, 1H, *p*-H in NPh, $^3J_{HH}$ = 7.0 Hz), 6.93−6.98 (m, 2H, H_{Ar}), 7.00−7.05 (m, 4H, H_{Ar}), 7.09−7.14 (m, 1H, H_{Ar}), 7.50−7.54 (m, 4H, H_{Ar}), 7.59−7.63 (m, 2H, H_{Ar}), 7.91 (dd, 4H, *o*-H in PPh_2, $^3J_{HP}$ = 11.9 Hz, $^3J_{HH}$ = 7.8 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 39.68 and 43.11 (both s, NMe_2), 119.67 (d, C6, $^4J_{CP}$ = 3.0 Hz), 121.22 (s, *p*-C in NPh), 125.30 (d, C5, $^3J_{CP}$ = 16.3 Hz), 126.49 (d, *o*-C in NPh, $^3J_{CP}$ = 11.6 Hz), 126.57 (d, C4, $^2J_{CP}$ = 20.7 Hz), 127.34 (s, *m*-C in NPh), 127.66 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 85.9 Hz), 128.88 (d, *m*-C in PPh_2, $^3J_{CP}$ = 11.9 Hz), 132.79 (d, *p*-C in PPh_2, $^4J_{CP}$ = 2.7 Hz), 133.36 (d, *o*-C in PPh_2, $^2J_{CP}$ = 10.1 Hz), 137.36 (d, C2, $^2J_{CP}$ = 22.9 Hz), 145.11 (d, C3, $^1J_{CP}$ = 139.9 Hz), 146.70 (d, *ipso*-C in NPh, $^2J_{CP}$ = 2.7 Hz), 152.26 (d, C1, $^3J_{CP}$ = 19.3 Hz), 176.54 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 476(w), 507(w), 522(m), 566(w), 612(w), 631(w), 693(m), 723(m), 740(m), 789(w), 806(w), 876(vw), 992(w), 1009(w), 1036(w), 1074(w), 1111(s), 1157(br, m), 1192(w), 1234(br, m), 1266(s) (νP═N), 1291(br, s), 1404(s), 1436(m), 1487(s), 1548(br, s) (νNC(S)O), 1572(m), 1591(m), 1618(w), 2855(vw), 2926(w), 3025(w), 3050(w), 3074(w). Anal. Calcd for $C_{27}H_{24}ClN_2OPPdS$: C, 54.28; H, 4.05; N, 4.69. Found: C, 54.34; H, 3.95; N, 4.51%.

Complex [κ^3-S,C,N-(L)Pd(II)Cl], ***11b****.*



Yield: 42 mg (57%) (method A); 118 mg (66%) (method B). Mp: >275 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 41.01 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 3.37 and 3.43 (both s, 3H + 3H, NMe_2), 6.99−7.08 (m, 4H, H_{Ar}), 7.14−7.19 (m, 1H, H_{Ar}), 7.55−7.59 (m, 4H, H_{Ar}), 7.65−7.69 (m, 2H, H_{Ar}), 7.79 (d, 2H, H_{Ar}, $^3J_{HH}$ = 8.9 Hz), 7.89 (ddd, 4H, *o*-H in PPh_2, $^3J_{HP}$ = 12.2 Hz, $^3J_{HH}$ = 7.8 Hz, $^4J_{HH}$ = 1.2 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 40.00 and 43.39 (both s, NMe_2), 120.32 (d, C6, $^4J_{CP}$ = 2.8 Hz), 123.71 (s, C9 and C11), 125.03 (d, C8 and C12, $^3J_{CP}$ = 13.8 Hz), 125.80 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 86.3 Hz), 126.03 (d, C5, $^3J_{CP}$ = 16.8 Hz), 127.14 (d, C4, $^2J_{CP}$ = 20.9 Hz), 129.55 (d, *m*-C in PPh_2, $^3J_{CP}$ = 12.2 Hz), 133.43 (d, *o*-C in PPh_2, $^2J_{CP}$ = 10.4 Hz), 133.76 (d, *p*-C in PPh_2, $^4J_{CP}$ = 2.6 Hz), 137.33 (d, C2, $^2J_{CP}$ = 21.4 Hz), 140.90 (s, C10), 144.58 (d, C3, $^1J_{CP}$ = 139.4 Hz), 152.17 (d, C1, $^3J_{CP}$ = 19.3 Hz), 155.12 (d, C7, $^2J_{CP}$ = 1.3 Hz), 176.66 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 479(w), 519(w), 550(w), 570(w), 624(vw), 671(w), 697(w), 727(w), 740(w), 752(w), 794(w), 843(w), 856(w), 992(w), 1111(m), 1160(w), 1184(w), 1233(w), 1277(s) (νP═N), 1287(s), 1301(s), 1338(w), 1351(w), 1408(w), 1437(w), 1491(m), 1549(br, m) (νNC(S)O), 1581(m), 2923(vw), 3055(vw). Raman (solid, $\Delta\nu$/cm^{-1}): 200(vw), 229(w), 257(vw), 313(w), 359(w), 390(vw), 407(vw), 448(w), 498(vw), 532(w), 551(w), 571(w), 625(w), 673(vw), 694(vw), 755(w), 794(w), 844(w), 858(m), 960(w), 993(m), 1029(w), 1076(vw), 1115(m), 1163(w), 1184(w), 1278(m) (νP═N), 1303(s), 1325(m), 1345(m), 1396(vw), 1425(vw), 1453(vw), 1504(vw), 1582(m), 3057(vw). Anal. Calcd for $C_{27}H_{23}ClN_3O_3PPdS$: C, 50.48; H, 3.61; N, 6.54. Found: C, 50.46; H, 3.61; N, 6.30%.

Complex [κ^3-S,C,N-(L)Pd(II)Cl], ***11c****.*



Yield: 62 mg (35%) (method B). Mp: >195 °C (dec.). $^{31}P\{^1H\}$ NMR (161.98 MHz, $CDCl_3$): δ 52.36 ppm. ^1H NMR (400.13 MHz, $CDCl_3$): δ 1.29 (s, 9H, $COOC(CH_3)_3$), 3.37 and 3.43 (both s, 3H + 3H, NMe_2), 3.99 (d, 2H, CH_2, $^3J_{HP}$ = 21.0 Hz), 6.94−7.00 (m, 2H, H_{Ar}), 7.04−7.09 (m, 1H, H_{Ar}), 7.50−7.54 (m, 4H, H_{Ar}), 7.60−7.63 (m, 2H, H_{Ar}), 7.82 (ddd, 4H, *o*-H in PPh_2, $^3J_{HP}$ = 11.5 Hz, $^3J_{HH}$ = 7.9 Hz, $^4J_{HH}$ = 1.4 Hz) ppm. $^{13}C\{^1H\}$ NMR (100.61 MHz, $CDCl_3$): δ 27.99 (s, $COOC(\underline{C}H_3)_3$), 39.93 and 43.13 (both s, NMe_2), 48.12 (d, CH_2, $^2J_{CP}$ = 1.4 Hz), 79.75 (s, $COO\underline{C}(CH_3)_3$), 120.12 (d, C6, $^4J_{CP}$ = 2.7 Hz), 125.17 (d, C5, $^3J_{CP}$ = 16.3 Hz), 126.64 (d, C4, $^2J_{CP}$ = 20.5 Hz), 128.86 (d, *ipso*-C in PPh_2, $^1J_{CP}$ = 84.9 Hz), 128.91 (d, *m*-C in PPh_2, $^3J_{CP}$ = 11.7 Hz), 132.72 (d, *p*-C in PPh_2, $^4J_{CP}$ = 2.4 Hz), 133.14 (d, *o*-C in PPh_2, $^2J_{CP}$ = 9.8 Hz), 137.16 (d, C2, $^2J_{CP}$ = 25.1 Hz), 143.54 (d, C3, $^1J_{CP}$ = 141.3 Hz), 152.45 (d, C1, $^3J_{CP}$ = 19.5 Hz), 171.85 (d, $\underline{C}OOC(CH_3)_3$, $^3J_{CP}$ = 8.2 Hz), 175.99 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 475(w), 515(w), 566(w), 607(w), 695(m), 722(m), 744(m), 783(w), 846(w), 900(w), 997(vw), 1111(m), 1151(s), 1215(w), 1246(m), 1283(m) (νP═N), 1302(m), 1366(w), 1404(m), 1436(m), 1483(w), 1549(br, m) (νNC(S)O), 1576(w), 1709(w), 1744(m) (νC═O), 2870(vw), 2929(w), 2975(w), 3053(vw). Anal. Calcd for $C_{27}H_{30}ClN_2O_3PPdS$: C, 51.03; H, 4.76; N, 4.41. Found: C, 51.09; H, 4.77; N, 4.21%.

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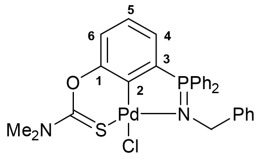
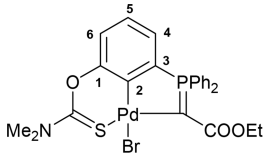
Organometallics XXXX, XXX, XXX−XXX

Complex [κ³-S,C,N-(L)Pd(II)Cl], ***11d****.*



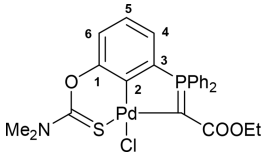
Yield: 77 mg (45%) (method B). Mp: >220 °C (dec.). $^{31}P\{^{1}H\}$ NMR (161.98 MHz, $CDCl_3$): δ 49.62 ppm. ^{1}H NMR (400.13 MHz, $CDCl_3$): δ 3.35 and 3.45 (both s, 3H + 3H, NMe_2), 4.55 (d, 2H, CH_2, $^{3}J_{HP}$ = 21.8 Hz), 6.98−7.13 (m, 6H, H_{Ar}), 7.24 (d, 2H, *o*-H in NPh, $^{3}J_{HH}$ = 7.0 Hz), 7.47−7.50 and 7.58−7.61 (both m, 4H + 2H, H_{Ar}), 7.78 (dd, 4H, *o*-H in PPh_2, $^{3}J_{HP}$ = 11.0 Hz, $^{3}J_{HH}$ = 7.8 Hz) ppm. $^{13}C\{^{1}H\}$ NMR (100.61 MHz, $CDCl_3$): δ 39.63 and 43.05 (both s, NMe_2), 48.85 (d, CH_2, $^{2}J_{CP}$ = 2.3 Hz), 119.74 (d, C6, $^{4}J_{CP}$ = 2.8 Hz), 125.14 (d, C5, $^{3}J_{CP}$ = 16.0 Hz), 125.43 (s, *p*-C in NPh), 126.54 (d, C4, $^{2}J_{CP}$ = 20.2 Hz), 127.37 and 127.79 (both s, *m*-C and *o*-C in NPh), 128.77 (d, *m*-C in PPh_2, $^{3}J_{CP}$ = 11.5 Hz), 128.86 (d, *ipso*-C in PPh_2, $^{1}J_{CP}$ = 83.5 Hz), 132.56 (d, *p*-C in PPh_2, $^{4}J_{CP}$ = 2.6 Hz), 133.08 (d, *o*-C in PPh_2, $^{2}J_{CP}$ = 9.8 Hz), 137.57 (d, C2, $^{2}J_{CP}$ = 23.8 Hz), 143.07 (d, *ipso*-C in NPh, $^{3}J_{CP}$ = 6.0 Hz), 143.79 (d, C3, $^{1}J_{CP}$ = 140.0 Hz), 152.37 (d, C1, $^{3}J_{CP}$ = 19.2 Hz), 176.40 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 473(w), 504(w), 570(m), 614(w), 694(s), 721(m), 742(s), 786(w), 863(w), 909(w), 969(w), 997(w), 1028(w), 1071(w), 1110(m), 1128(w), 1159(m), 1245(m), 1281(m) (νP═N), 1300(s), 1354(w), 1403(s), 1435(m), 1451(w), 1483(w), 1493(w), 1550(br, s) (νNC(S)O), 1576(w), 2850(w), 2923(w), 3024(w), 3052(w). Anal. Calcd for $C_{28}H_{26}ClN_2OPPdS$: C, 55.00; H, 4.29; N, 4.58. Found: C, 55.09; H, 4.14; N, 4.45%.

Complex [κ³-S,C,C-(L)Pd(II)Br], ***12a-Br****.*



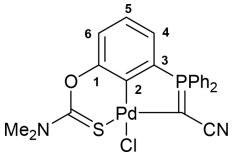
A solution of phosphonium bromide **6a** (124 mg, 0.233 mmol) and Et_3N (65 μL, 0.466 mmol) in benzene (5 mL) was stirred at room temperature under an argon atmosphere for 1 h. Then, a solution of $PdCl_2(NCPh)_2$ (89 mg, 0.233 mmol) in dichloromethane (2.5 mL) was added dropwise to the resulting mixture bearing *in situ* generated phosphonium ylide. The reaction mixture was left under ambient conditions for 1 day and evaporated to dryness. The residue obtained was purified by column chromatography on silica gel (elution with neat $CHCl_3$ and $CHCl_3$−EtOH mixture (100:1)) to give 107 mg of complex **12a-Br** as a light-yellow crystalline solid. Yield: 72%. Mp: >265 °C (dec.). $^{31}P\{^{1}H\}$ NMR (161.98 MHz, $CDCl_3$): δ 23.37 ppm. ^{1}H NMR (400.13 MHz, $CDCl_3$): δ 1.15 (t, 3H, $COOCH_2C\underline{H}_3$, $^{3}J_{HH}$ = 7.1 Hz), 3.36 and 3.45 (both s, 3H + 3H, NMe_2), 4.01−4.09 (m, 2H, $COOC\underline{H}_2CH_3$), 4.15 (d, 1H, CHP, $^{2}J_{HP}$ = 2.2 Hz), 7.07 (d, 1H, H(C6), $^{3}J_{HH}$ = 7.7 Hz), 7.20−7.30 (m, 2H, H_{Ar}), 7.48−7.66 (m, 6H, H_{Ar}), 7.81 (dd, 2H, *o*-H in PPh, $^{3}J_{HP}$ = 11.7 Hz, $^{3}J_{HH}$ = 7.5 Hz), 7.98 (dd, 2H, *o*-H in PPh, $^{3}J_{HP}$ = 12.2 Hz, $^{3}J_{HH}$ = 7.3 Hz) ppm. $^{13}C\{^{1}H\}$ NMR (100.61 MHz, $CDCl_3$): δ 14.31 (s, $COOCH_2\underline{C}H_3$), 30.05 (d, CHP, $^{1}J_{CP}$ = 58.0 Hz), 39.70 and 43.30 (both s, NMe_2), 60.10 (s, $COO\underline{C}H_2CH_3$), 120.66 (d, C6, $^{4}J_{CP}$ = 3.0 Hz), 125.51 (d, *ipso*-C in PPh, $^{1}J_{CP}$ = 89.4 Hz), 125.87 (d, C5, $^{3}J_{CP}$ = 15.2 Hz), 126.37 (d, *ipso*-C in PPh, $^{1}J_{CP}$ = 69.6 Hz), 128.81 (d, *m*-C in PPh, $^{3}J_{CP}$ = 11.5 Hz), 129.04 (d, C4, $^{2}J_{CP}$ = 16.0 Hz), 129.43 (d, *m*-C in PPh, $^{3}J_{CP}$ = 12.0 Hz), 132.88 (d, *p*-C in PPh, $^{4}J_{CP}$ = 2.7 Hz), 132.96 (d, *p*-C in PPh, $^{4}J_{CP}$ = 2.5 Hz), 132.99 (d, *o*-C in PPh, $^{2}J_{CP}$ = 9.2 Hz), 134.13 (d, *o*-C in PPh, $^{2}J_{CP}$ = 9.9 Hz), 141.91 (d, C3, $^{1}J_{CP}$ = 118.3 Hz), 145.52 (d, C2, $^{2}J_{CP}$ = 25.9 Hz), 152.69 (d, C1, $^{3}J_{CP}$ = 21.3 Hz), 172.33 (d, $\underline{C}OOCH_2CH_3$, $^{2}J_{CP}$ = 1.2 Hz), 177.71 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 473(w), 518(w), 541(m), 566(w), 691(w), 722(w), 739(m), 784(w), 830(br, w) and 862(br, w) (both νP═C), 998(w), 1042(w), 1110(m), 1136(s), 1150(m), 1190(w), 1229(s)/1239(s), 1279(m), 1294(s), 1365(w), 1405(s), 1436(s), 1460(w), 1483(w), 1552(br, s) (νNC(S)O), 1576(w), 1676(m) and 1692(s) (both νC═O), 2929(w), 2974(w), 3054(w). Anal. Calcd for $C_{25}H_{25}BrNO_3PPdS$: C, 47.15; H, 3.96; N, 2.20. Found: C, 47.04; H, 3.91; N, 2.17%.

Complex [κ³-S,C,C-(L)Pd(II)Cl], ***12a-Cl****.*



A solution of phosphonium bromide **6a** (101 mg, 0.190 mmol) and Et_3N (53 μL, 0.380 mmol) in benzene (5 mL) was stirred at room temperature under an argon atmosphere for 1 h. The resulting reaction mixture, bearing *in situ* generated phosphonium ylide, was filtered. The precipitate was additionally rinsed with benzene (3 mL). Then, a solution of $PdCl_2(NCPh)_2$ (73 mg, 0.190 mmol) in dichloromethane (4 mL) was added dropwise. The reaction mixture was left under ambient conditions for 1 day and evaporated to dryness. The resulting residue was purified by column chromatography on silica gel (gradient elution with neat $CHCl_3$ and $CHCl_3$−EtOH mixture (from 100:1 to 50:1)) to give 46 mg of complex **12a-Cl** as a light-yellow crystalline solid.[36] Yield: 41%. Mp: >240 °C (dec.). $^{31}P\{^{1}H\}$ NMR (161.98 MHz, $CDCl_3$): δ 21.77 ppm. ^{1}H NMR (400.13 MHz, $CDCl_3$): δ 1.16 (t, 3H, $COOCH_2C\underline{H}_3$, $^{3}J_{HH}$ = 7.1 Hz), 3.38 and 3.47 (both s, 3H + 3H, NMe_2), 4.00−4.10 (m, 3H, CHP + $COOC\underline{H}_2CH_3$), 7.06 (d, 1H, H(C6), $^{3}J_{HH}$ = 7.2 Hz), 7.19−7.31 (m, 2H, H_{Ar}), 7.49−7.66 (m, 6H, H_{Ar}), 7.83 (dd, 2H, *o*-H in PPh, $^{3}J_{HP}$ = 11.7 Hz, $^{3}J_{HH}$ = 7.6 Hz), 7.98 (dd, 2H, *o*-H in PPh, $^{3}J_{HP}$ = 12.1 Hz, $^{3}J_{HH}$ = 7.3 Hz) ppm. $^{13}C\{^{1}H\}$ NMR (100.61 MHz, $CDCl_3$): δ 14.32 (s, $COOCH_2\underline{C}H_3$), 30.92 (d, CHP, $^{1}J_{CP}$ = 59.0 Hz), 39.61 and 43.28 (both s, NMe_2), 60.09 (s, $COO\underline{C}H_2CH_3$), 120.48 (d, C6, $^{4}J_{CP}$ = 3.0 Hz), 125.58 (d, *ipso*-C in PPh, $^{1}J_{CP}$ = 78.7 Hz), 125.73 (d, C5, $^{3}J_{CP}$ = 15.1 Hz), 126.37 (d, *ipso*-C in PPh, $^{1}J_{CP}$ = 59.2 Hz), 128.80 (d, *m*-C in PPh, $^{3}J_{CP}$ = 11.6 Hz), 129.05 (d, C4, $^{2}J_{CP}$ = 15.9 Hz), 129.44 (d, *m*-C in PPh, $^{3}J_{CP}$ = 12.1 Hz), 132.86 (d, *p*-C in PPh, $^{4}J_{CP}$ = 2.7 Hz), 132.93−133.02 (overlapping signals of *p*-C + *o*-C in PPh), 134.17 (d, *o*-C in PPh, $^{2}J_{CP}$ = 10.0 Hz), 142.34 (d, C3, $^{1}J_{CP}$ = 118.4 Hz), 144.17 (d, C2, $^{2}J_{CP}$ = 25.9 Hz), 153.06 (d, C1, $^{3}J_{CP}$ = 21.3 Hz), 172.33 (d, $\underline{C}OOCH_2CH_3$, $^{2}J_{CP}$ = 1.3 Hz), 178.13 (s, C═S) ppm. IR (KBr, ν/cm^{-1}): 475(w), 518(w), 541(m), 566(w), 692(m), 722(w), 740(m), 785(vw), 830(br, w) and 858(br, w) (both νP═C), 998(w), 1042(w), 1100(m), 1137(s), 1158(m), 1190(w), 1231(br, s), 1294(s), 1365(w), 1404(s), 1436(s), 1483(w), 1552(br, s) (νNC(S)O), 1576(w), 1649(w), 1674(sh, m) and 1692(s) (both νC═O), 2930(w), 2974(w), 3054(w). Anal. Calcd for $C_{25}H_{25}ClNO_3PPdS$: C, 50.69; H, 4.25; N, 2.36. Found: C, 50.54; H, 4.14; N, 2.21%.

Complex [κ³-S,C,C-(L)Pd(II)Cl], ***12b****.*



A solution of phosphonium chloride **6b** (78 mg, 0.177 mmol) and Et_3N (50 μL, 0.360 mmol) in benzene (4 mL) was stirred at room temperature under an argon atmosphere for 15 min. Then, a solution of $PdCl_2(NCPh)_2$ (68 mg, 0.177 mmol) in dichloromethane (2 mL) was added dropwise to the resulting mixture bearing *in situ* generated phosphonium ylide. The reaction mixture was left under ambient conditions for 1 day and evaporated to dryness. The resulting residue was purified by column chromatography on silica gel (gradient elution with neat $CHCl_3$ and $CHCl_3$−EtOH mixture (from 100:1 to 50:1)) and recrystallized from $CHCl_3$−hexane to give 48 mg of complex **12b** as a whitish crystalline solid. Yield: 50%. Mp: >300 °C (dec.). $^{31}P\{^{1}H\}$ NMR (161.98 MHz, $CDCl_3$): δ 24.63 ppm.[37] ^{1}H NMR (400.13 MHz, $CDCl_3$): δ 3.44 and 3.51 (both s, 3H + 3H, NMe_2), 7.14−7.18 (m, 1H, CHP + 1H, H_{Ar}), 7.24−7.28 (m, 2H, H_{Ar}), 7.58−7.66 (4H, H_{Ar}), 7.71−7.76 (m, 4H, H_{Ar}), 7.92 (dd, 2H, *o*-H in PPh, $^{3}J_{HP}$ = 12.9 Hz, $^{3}J_{HH}$ = 7.3 Hz) ppm. $^{13}C\{^{1}H\}$ NMR (100.61 MHz, $(CD_3)_2SO$): δ 8.84 (d, CHP, $^{1}J_{CP}$ = 52.7 Hz), 43.45 (s, NMe), 120.45

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Organometallics XXXX, XXX, XXX−XXX

Table 4. Crystal Data and Structure Refinement Parameters for Complexes 7−9, 11a, 11c,d, 12a-Br, 12a-Cl, and 13b

	7	8	9	11a	11c	11d	12a-Br	12a-Cl	12b
Empirical formula	$C_{22\cdot86}H_{24\cdot45}Cl_{1\cdot27}NO_{1\cdot86}PPdS_2$	$C_{22}H_{21}Cl_3NOPPdSSe$	$C_{44}H_{40}Cl_8N_2O_4P_2Pd_2S_2$	$C_{27}H_{24}ClN_2OPPdS$	$C_{28}H_{31}Cl_4N_2O_3PPdS$	$C_{57}H_{54}Cl_4N_4O_2P_2Pd_2S_2$	$C_{25}H_{25}BrNO_3PPdS$	$C_{25}H_{25}ClNO_3PPdS$	$C_{25}H_{26}ClN_2O_2PPdS$
Formula weight	589.72	670.14	1283.24	597.36	754.78	1307.70	636.80	592.34	591.36
T (K)	120	120	120	120	120	120	120	120	120
Crystal system	Orthorhombic	Orthorhombic	Monoclinic	Monoclinic	Triclinic	Triclinic	Monoclinic	Monoclinic	Monoclinic
Space group	$Pca2_1$	$Pca2_1$	$P2_1/c$	$P2_1/c$	P-1	P-1	$P2_1/n$	$P2_1/n$	$P2_1/n$
Z	4	4	4	8	2	2	4	4	4
a (Å)	15.0712(7)	15.2588(5)	18.2420(19)	21.5810(16)	10.3402(6)	13.146(2)	8.9796(12)	8.9630(7)	8.3841(6)
b (Å)	8.4975(4)	8.7929(3)	18.678(2)	14.2260(11)	10.8771(6)	14.791(3)	17.908(2)	17.4280(14)	22.8524(18)
c (Å)	18.5123(8)	18.0504(6)	15.2640(16)	17.8919(14)	17.1584(10)	16.483(3)	15.792(2)	15.9966(13)	13.2418(10)
α (deg)	90	90	90	90	101.7410(10)	97.597(4)	90	90	90
β (deg)	90	90	109.663(2)	114.4490(10)	96.2650(10)	109.953(4)	103.133(3)	105.324(2)	103.847(2)
γ (deg)	90	90	90	90	118.2160(10)	108.489(4)	90	90	90
V (Å^3)	2370.82(19)	2421.81(14)	4897.5(9)	5000.5(7)	1617.09(16)	2751.0(8)	2473.1(6)	2409.9(3)	2463.4(3)
D_{calc} (g cm^{-1})	1.652	1.838	1.740	1.587	1.550	1.579	1.710	1.633	1.595
Linear absorption, μ (cm^{-1})	11.91	27.69	13.66	10.2	10.5	10.29	25.43	10.62	10.37
F(000)	1193	1320	2560	2416	764	1324	1272	1200	1200
$2\theta_{max}$ (deg)	56	58	54	54	58	56	52	54	56
No. of reflns measd	17333	28018	85231	51844	19700	32078	15089	41991	20454
No. of independent reflns	5697	6417	10692	10904	8588	13277	4837	5267	5927
No. of observed reflns [$I > 2\sigma(I)$]	5315	5957	7695	9136	7528	8618	3716	4126	4300
Parameters	310	282	588	618	366	662	301	301	301
R1	0.0241	0.0220	0.0568	0.0364	0.0304	0.0503	0.0963	0.0511	0.0431
wR2	0.0504	0.0436	0.1815	0.0733	0.0642	0.1121	0.2548	0.1515	0.1005
GOF	1.005	0.950	1.149	1.021	1.049	0.998	1.575	1.044	1.002
$\Delta\rho_{max}/\Delta\rho_{min}$ (e Å^{-3})	0.481/-0.297	0.443/-0.312	2.338/-1.780	0.721/-1.379	0.525/-0.679	0.757/-1.148	2.929/-1.412	1.243/-1.554	1.597/-0.829

(d, CN, $^2J_{CP}$ = 6.2 Hz), 122.66 (d, C6, $^4J_{CP}$ = 2.8 Hz), 123.55 (d, *ipso*-C in PPh, $^1J_{CP}$ = 90.3 Hz), 125.13 (d, *ipso*-C in PPh, $^1J_{CP}$ = 69.6 Hz), 127.53 (d, C5, $^3J_{CP}$ = 15.1 Hz), 130.09 (d, *m*-C in PPh, $^3J_{CP}$ = 11.2 Hz), 130.17 (d, *m*-C in PPh, $^3J_{CP}$ = 12.4 Hz), 133.27 (d, *o*-C in PPh, $^2J_{CP}$ = 10.0 Hz), 133.32 (d, *o*-C in PPh, $^2J_{CP}$ = 9.5 Hz), 134.37 (d, *p*-C in PPh, $^4J_{CP}$ = 2.7 Hz), 134.51 (d, *p*-C in PPh, $^4J_{CP}$ = 2.7 Hz), 138.91 (d, C3, $^1J_{CP}$ = 116.5 Hz), 153.53 (d, C1, $^3J_{CP}$ = 21.2 Hz), 176.46 (s, C═S) ppm (the signal of the second NMe carbon nucleus was not assigned due to overlapping with the solvent signal, the signals of C2 and C5 carbon nuclei were not observed). IR (KBr, ν/cm^{-1}): 456(w), 480(w), 501(w), 511(m), 537(w), 571(w), 586(w), 615(vw), 686(w), 726(w), 738(m), 751(w), 787(w), 845(br, w) (νP═C), 997(w), 1106(m), 1117(m), 1159(m), 1189(w), 1247(s), 1283(m), 1294(s), 1337(vw), 1406(s), 1436(s), 1486(w), 1558(br, s) (νNC-(S)O), 1576(m), 2193(m) and 2202(m) (both νC≡N), 2927(vw), 3055(w). Anal. Calcd for $C_{23}H_{20}ClN_2OPPdS$: C, 50.66; H, 3.70; N, 5.14. Found: C, 50.37; H, 3.58; N, 5.02%.

Solid-Phase Cyclopalladation. Ligand **2**−**4**, **5a**, or **5b** (0.112 mmol) and $PdCl_2(NCPh)_2$ (43 mg, 0.112 mmol) were manually ground in a mortar for several minutes. In the case of compounds **2**, **3**, **5a**, and **5b**, the resulting mixture was left in a closed test tube for 1 day (**5a**) or heated in an open test tube at the specified temperature (see Scheme 8) for 5 min to give a dark-yellow (**2**) or brown (**3**, **5a**, **5b**) powder, which was analyzed by IR and, in most cases, Raman spectroscopy (without any workup and/or after rinsing with Et_2O and hexane to remove residual benzonitrile) (Figures S30−S52). Heating of the homogenized mixture of ligand **4** and $PdCl_2(NCPh)_2$ at 90 °C for 10 min afforded a brown residue. According to the ^{31}P NMR spectrum (in $CDCl_3$/$(CD_3)_2SO$), it contained 10% target pincer complex **8**. The reaction temperatures were optimized by preliminary heating of samples of the homogenized mixtures on an MPA 120 EZ-Melt Automated Melting Point Apparatus (Stanford Research Systems) and corresponded to the expected changes in the phase state (melting followed by solidification at the higher temperature) and the release of HCl vapor detected with a paper indicator (in the case of ligands **2** and **3**).

Cytotoxicity Assays. The cytotoxic activities of complexes **7**, **8**, **11b**, **11d**, and **12a-Cl** were tested against human colon cancer cell line HCT116, human breast cancer cell line MCF7, human prostate cancer cell line PC3, and normal human embryonic kidney cells HEK293. RPMI-1640 and DMEM media were obtained from Gibco. Fetal bovine serum (FBS) was purchased from HyClone. Cells were cultured in RPMI-1640 (in the case of PC3) or DMEM (in the other cases) media supplemented with 10% FBS, 100 units/L penicillin, and 100 μg/mL streptomycin in a humidified incubator with 5% CO_2 atmosphere. The effect of the compounds on cell viability was evaluated by the standard MTT assay (ICN Biomedicals, Germany). Cells were seeded in triplicate at a cell density of 5×10^3/well in 96-well plates in 100 μL of complete medium and preincubated for 24 h. The tested compounds were initially dissolved in DMSO. Then, the compounds at various concentrations were added to the media. The well plates were incubated for 48 h followed by addition of MTT solution (Sigma) (20 μL, 5 mg/mL). The cells were incubated at 37 °C for a further 3 h; then, the culture medium was removed, and formazan crystals were dissolved in DMSO (70 μL). The absorbance of the resulting solutions was measured on a multiwell plate reader (Uniplan, Picon, Russia) at 590 nm to determine the percentage of surviving cells. The reported values of IC_{50} are the averages of three independent experiments (Table 3).

X-ray Diffraction. Single crystals suitable for X-ray analysis were obtained by slow diffusion of EtOH into CH_2Cl_2 solution of **7**, EtOAc into $CHCl_3$−CH_2Cl_2 solution of **9**, Et_2O into MeCN solution of **11a**,

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Organometallics XXXX, XXX, XXX−XXX

hexane into $CHCl_3$ solution of **11c**, EtOH into DMSO solution of **12b**, EtOAc (**8**, **12a-Br**, **12a-Cl**) or Et_2O (**11d**) into CH_2Cl_2 solutions of the mentioned complexes. X-ray diffraction experiments were carried out with a Bruker APEX2 CCD diffractometer (for **8**, **11a**, **11c**,**12a-Br**, and **12b**) and with a Bruker APEX2 DUO CCD diffractometer (for **7**, **9**, **11d**, and**12a-Cl**), using the graphite monochromated Mo Kα radiation (l = 0.71073 Å, ω-scans) at 120 K. The structures were solved by direct method and refined by the full-matrix least-squares against F^2 in anisotropic approximation for non-hydrogen atoms. Hydrogen atoms of the OH groups of the ethanol molecules in **7** and **12b** were located from difference Fourier synthesis; positions of the others were calculated. All hydrogen atoms were then refined in the isotropic approximation in the riding model. Crystal data and structure refinement parameters for the compounds explored are given in Table 4. All calculations were performed using the SHELXTL software.[38]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.8b00867.

Synthesis of 3-diphenylselenophosphorylphenol; ^1H, $^{13}C\{^1H\}$, COSY, HMQC, and HMBC NMR spectra of ligand **3** and complex **8**; IR and Raman spectra of compounds **2**, **3**, **5a**, **5b**, **7**, **8**, **11a**, and **11b**; IR and Raman spectra of the solid residues obtained after solvent-free reactions of ligands **2**, **3**, **5a**, and **5b** with $PdCl_2(NCPh)_2$ (PDF)

Accession Codes

CCDC 1563513−1563521 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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