Interaction of Palladium(II) Complexes with Amino-Alcohols: Synthesis of New Amino-Carbonyl Complexes, Key Intermediates to Cyclic Carbamates

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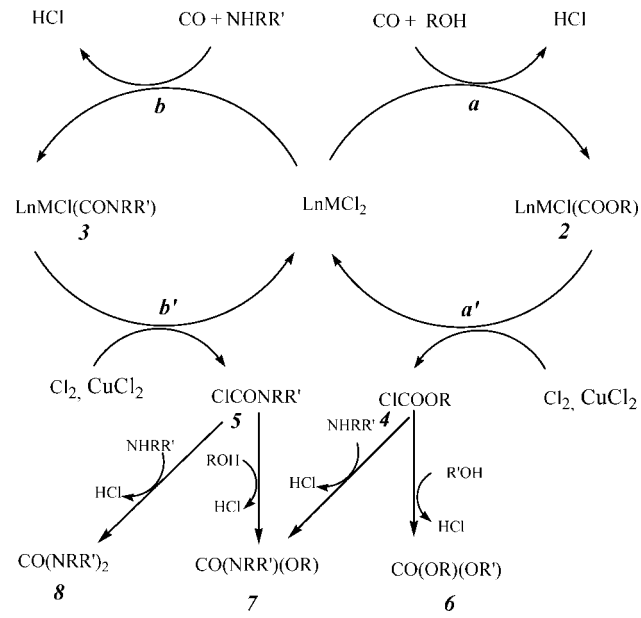
The interaction between carbon monoxide and aromatic or aliphatic amino-alcohols promoted by some palladium(II) tetracoordinated complexes, stabilized by aryl mono- and diphosphines [triphenylphosphine (PPh_3); 1,2-bis(diphenylphosphine)ethane (dppe)], an amino-phosphine [(2-(β-diphenylphosphino)ethylpyridine) (PN)], and diamines [2,2′-dipyridine (dipy); 1,10-phenanthroline (phen)], was investigated. All tested complexes and substrates were shown to interact with CO to afford either stable carbamoyl complexes, which were isolated and studied for their reactivity, or, directly, organic products. From the reaction of $PdCl_2$(PN) with 4-aminophenol (4-APhOH, **a**) the stable carbamoyl complex (PN)PdCl($CONHC_6H_4$-OH), able to release the amino-carbonyl ligand as isocyanate HOC_6H_4NCO, was isolated. The aliphatic amino-alcohols H_2N-R-OH [2-aminoethanol (2-AE, **b**); 1-amino-2-propanol (1-A2P, **c**); 3-aminopropanol (3-AP, **d**); 2-aminobutanol (2-A1B, **e**); 4-aminobutanol (4-AB, **f**); 5-aminopentanol (5-APE, **g**); 6-aminohexanol (6-AHX, **h**)] were reacted with all Pd complexes described above, but only when the triphenylphosphine ligand was used was it possible to isolate the stable carbamoyl complexes ($PPh_3)_2$PdCl(CONH-R-OH). The Pd(II) complexes with other ligands reacted in the same way, but the relevant intermediate complexes decomposed during the progress of the reaction, giving a mixture of cyclic carbamates and ureas and the relevant Pd(0) complex, "Pd-L" (L = PN, dppe, dipy, phen), which converted into Pd-black and the free ligand. Carbamoyl complexes with an aliphatic amino-alcohol bearing a primary amine are unprecedented in the literature. They were characterized by means of IR and NMR spectroscopy and studied for their reactivity. All the complexes upon simple heating or by reaction with I_2 or $CuCl_2$ release the amino-carbonyl function as cyclic carbamate and/or urea, depending on the complex and the presence or absence of the free amino-alcohol in solution.

1. Introduction

It is well known that transition metal ions, in the presence or absence of ancillary ligands, are able to promote the oxidative carbonylation of alcohols or amines to give carbonates (**6**), carbamates (**7**), and ureas (**8**), products of industrial interest. Alkoxy-carbonyl (LnMClCOOR, **2**) or amino-carbonyl complexes (LnMXCONRR′, **3**) (Scheme 1) are key intermediates to carbamates, ureas, or carbonates. If sufficiently stabilized by suitable ancillary ligands, they can be isolated and studied for their reactivity.

Following the reaction path shown in Scheme 1, we have synthesized several nickel[1,2] and palladium[3–6] alkoxy-carbonyl or amino-carbonyl complexes. We have shown that by further reaction with chlorine donors ($CuCl_2$, Cl_2) they release either the alkoxy-carbonyl or the amino-carbonyl moiety as chloroformate (**4**, route a′) or chloroformamide (**5**, route b′),

Scheme 1. Routes to the Synthesis of Alkoxy-Carbonyl or Amino-Carbonyl Pd (Ni) Complexes and Their Conversion into Carbonyl Organic Products



respectively.[3–6] The latter compounds react in situ with alcohols or amines to afford the desired carbonylic products **6**, **7**, and **8**.

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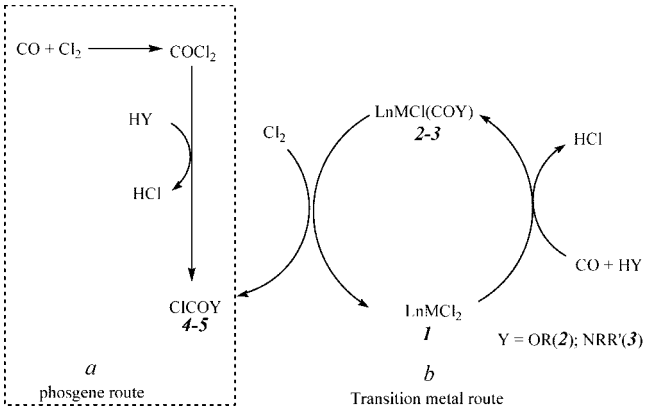
Scheme 2. Comparison of the Phosgene Route with the Methodology Based on the Use of Transition Metal Catalysts for the Synthesis of Chloroformates or Chloroformamides



The reaction mechanisms depicted in Scheme 1 were demonstrated by us in 1993.[3] This process is an alternative procedure to the use of phosgene (Scheme 2a), banned in most countries.

It is worth noting that both the traditional phosgene route and the methodology we have described in previous papers and in the present one use the same reagents (Cl_2 or $CuCl_2$, CO, ROH, NH_2R), but the former technology requires the handling and the eventual storage of the toxic and harmful phosgene, while the transition metal based procedure (Scheme 2b) avoids the synthesis of the toxic intermediate (Scheme 2a).

Very recently,[7] we have found that $PdCl_2(PN)$ (PN = 2-(β-diphenylphosphino)ethylpyridine) is effective in the promotion of the alkoxy-carbonylation of dialcohols (HO-R-OH). We have been able to synthesize and characterize the first alkoxy-carbonyl complexes [(PdClPN(COO-R-OH)] with such substrates. As expected, they react with $CuCl_2$ or Cl_2 and give rise to the relevant chloroformates, which, in the presence of NEt_3, in situ convert into cyclic carbonates, by intramolecular nucleophilic attack of the OH group on the carboxylic carbon.

The present work was undertaken in order to ascertain if the ligand PN or other P, P-P, or N-N ligands were able to promote the palladium-catalyzed carbonylation of amino-alcohols (H_2N-R-OH). In this case, two types of organometallic intermediates (Scheme 3) would in principle be formed, namely, the alkoxy-carbonyl [(LnPdCl(COO-RNH_2)] (**9**) or the amino-carbonyl complex [LnPdCl(CONH-ROH)] (**10**), originated by carbonylation of the −OH or NH_2 moiety, respectively. Both **9** and **10** eventually react to afford heterocyclic organic compounds, such as cyclic carbamates (**11**): only **10** would produce ureas (**12**) in presence of free amino-alcohol in solution.

2. Results and Discussion

$PdCl_2PN$ promotes the carbonylation of aromatic and aliphatic amino-alcohols H_2N-R-OH under mild conditions [(H_2N-R-OH) = 4-aminophenol (4-APhOH, **a**); 2-aminoethanol (2-AE, **b**); 1-amino-2-propanol (1-A2P, **c**); 3-aminopropanol (3-AP, **d**); 2-aminobutanol (2-AB, **e**); 4-aminobutanol (4-AB, **f**); 5-aminopentanol (5-APE, **g**); 6-aminohexanol (6-AHX, **h**)]. By reacting 4-APhOH, the carbamoyl complex $PdCl(CONHC_6H_4OH)(PN)$ (**10a** Scheme 3) was isolated, indicating that the NH_2 group is a better nucleophile than −OH (eq 1)

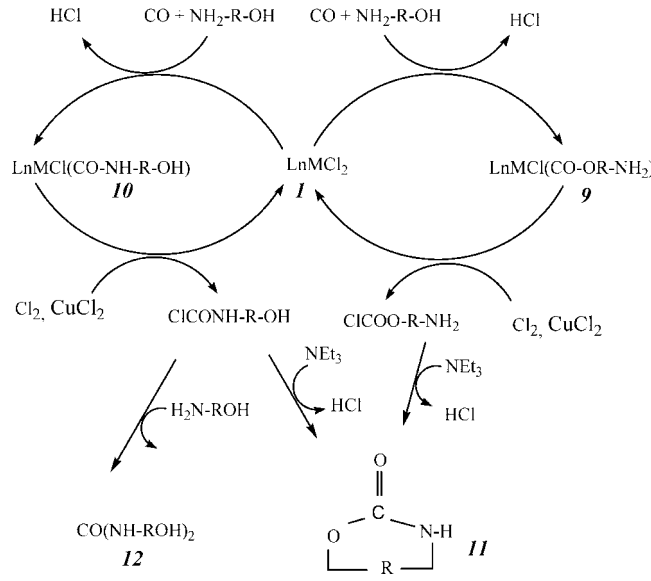
$$PdCl_2(PN) + H_2N\text{-}C_6H_4\text{-}OH + CO \rightarrow PdCl(CONH\text{-}C_6H_4\text{-}OH)(PN) + HCl \quad (1)$$

The hydrogen chloride produced in the reaction was neutralized by the same amino substrate, as shown by the presence of $OH\text{-}C_6H_4NH_3^+Cl^-$ in the reaction medium.

Attempts to isolate the relevant alkoxycarbonyl complex $PdCl(CO\text{-}OC_6H_4\text{-}NH_2)(PN)$ (**9a**) by carrying out the reaction under different conditions, including the addition of NEt_3, were unsuccessful. Under these conditions, the addition of a tertiary amine produces the formation of metallic palladium and a mixture of organic products containing 1,3-bis(4-hydroxyphenyl)urea as the main product, which was characterized by NMR and elemental analysis (see Experimental Section).

The 2-AE, 1-A2P, 3-AP, 2-A1B, 4-AB, 5-APE, and 6-AHX aliphatic amino-alcohols (H_2N-R-OH) react in the same way, under the same temperature and pressure conditions, giving the relevant carbamoyl complexes, (PN)PdCl(CONH-R-OH), which, being much more reactive than $(PN)PdCl(CONHC_6H_4OH)$, could not be isolated as pure compounds. They evolve in the reaction medium yielding mainly heterocyclic organic compounds (**11**), evidenced by the presence in the IR spectrum of the reaction solution of an absorption band between 1762 and 1708 cm^{-1} and by the GC-MS spectra (see below). Moreover, the presence of carbamoyl intermediates in the reaction medium was well documented analyzing the solid products recovered in the course of the reaction. For instance, when the reaction between $PdCl_2PN$ and 1-A2P was stopped after ca. 50–60% of conversion [based on the CO reacted (molar ratio CO/Pd = 0.5–0.6)], the reactivity of the filtered solid from the reaction mixture was consistent with two compounds: the initial unreacted $PdCl_2PN$ complex and the formed unstable intermediate carbamoyl complex. The carbamoyl complex in the solid product was evidenced by its IR spectrum, which showed an absorption band at 1620 cm^{-1}, attributable to the CO of the carbamoyl moiety. Support for its presence came from the appearance in solution of a band at 1761 cm^{-1}, due to the five-membered cyclic carbamate 5-methyl-2-oxazolidinone, confirmed by its GC-MS-spectrum, obtained by heating the solid of reaction in CH_3CN under a dinitrogen atmosphere in the presence of NEt_3 (Scheme 4).

Scheme 3. Alternative N- or O-Carbonylation by Reaction of Amino-Alcohols with CO Promoted by Metal Centers Stabilized by Ligands



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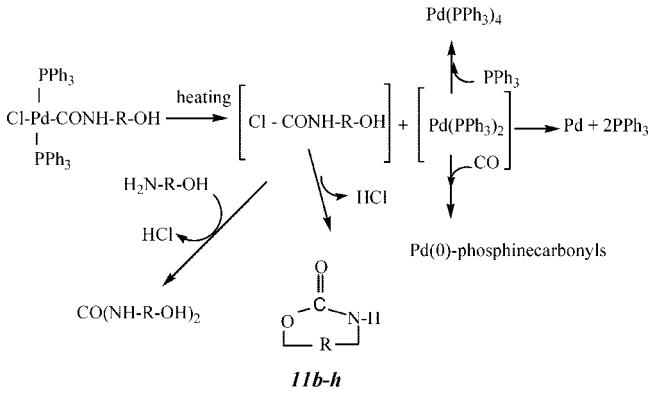
Scheme 4. Thermal Decomposition of Pd-Carbamoyl Complexes



11b-h

The higher ability of the amino group of the amino alcohol to interact with the CO coordinated to a metal center, observed in this study, is in line with a recent result on the oxidative carbonylation of amino-alcohols catalyzed by $W(CO)_6$, whose selective conversion into ureas can be justified through the formation of a carbamoyl intermediate complex.[8] Also, 2-AE has been shown to react with CO and $PdCl_2(PMe_3)_2$ to afford a carbamoyl complex that has been characterized by X-ray.[9]

In an attempt to obtain pure and more stable carbamoyl complexes with aliphatic amino-alcohols and with the aim to study the reactivity of the amino-carbonyl function, we have investigated the reactivity of other tetracoordinated palladium complexes, $PdCl_2Ln$ (Ln = PPh_3; dppe; dipy; *o*-phen). A preliminary screening showed that, among those tested, the triphenylphosphine complex $PdCl_2(PPh_3)_2$ was able to give more stable carbamoyl derivatives. Thus, our attention was devoted to the derivatives of this complex, which were isolated, characterized, and studied for their reactivity.

The carbamoyl complexes of formula $PdCl(CO\text{-}NH\text{-}R\text{-}OH)(PPh_3)_2$ (**10b**−**h**) were isolated in appreciable yields (50–70%) by reacting $PdCl_2(PPh_3)_2$ with aliphatic amino-alcohols [2-AE (**b**); 1-A2P (**c**); 3-AP (**d**); 2-A1B (**e**); 4-AB (**f**); 5-APE (**g**); 6-AHX (**h**)], in CH_3CN under CO at atmospheric pressure and room temperature (eq 2).

$$PdCl_2(PPh_3)_2 + 2H_2N\text{-}R\text{-}OH + CO \rightarrow PdCl(PPh_3)_2(CO\text{-}NH\text{-}R\text{-}OH)(\mathbf{10b}-\mathbf{h}) + OH\text{-}R\text{-}NH_2{\cdot}HCl \quad (2)$$

The crude complexes had impurities of ammonium salts or, in some cases, of ureas. After crystallization they could be isolated as pure compounds and in appreciable yields (50–70%), as white-cream microcrystalline products. They were stable in the solid state and could be manipulated in the air without any modification.

Carbamoyl complexes of amino-alcohols with a primary amino group are unprecedented in the literature, and to the best of our knowledge, only two carbamoyl complexes of amino-alcohols with secondary amino groups were described so far.[9]

The isolated complexes (**10a**−**h**) were fully characterized by elemental analysis and IR and NMR spectroscopy. The decomposition reaction with HCl and the characterization of organic products formed upon evolution of the amino-carbonyl moiety completed their characterization. The IR spectra in Nujol mull show characteristic absorption bands attributable to the stretching of O−H and N−H (3577–3174 cm^{-1}), C═O (1620–1589 cm^{-1}), and C−N (1203–1182 cm^{-1}) of the amino-carbonyl group. The observed frequencies (see the Experimental Section) are consistent with those found for other carbamoyl complexes.[5,6,9,10]

Table 1. Characterization of Complexes by Decomposition with HCl: CO Evolved

complex	mmol	*V*(CO) (mL)	CO (mmol)
10c	0.26	5.5	0.24
10e	0.24	5.6	0.25
10f	0.19	4.0	0.18
10g	0.23	4.7	0.21
10h	0.19	3.8	0.17
10a	0.18	3.8	0.17

The complexes are stable at room temperature in the presence of weak acids but decompose smoothly with mineral acids upon heating. The reaction with HCl was also exploited for their characterization, as they undergo a back-reaction and develop one mole of CO per mole of complex (eq 3 and Table 1).

$$PdCl(PPh_3)_2(CO\text{-}NH\text{-}R\text{-}OH) + HCl \rightarrow PdCl_2(PPh_3)_2 + HO\text{-}R\text{-}NH_2{\cdot}HCl + CO \quad (3)$$

The gas evolved was measured with a gas burette and identified as CO by GC analysis.

The complex $Cl(PN)Pd\text{-}C(O)NHC_6H_4OH$ (**10a**) was characterized in DMSO by means of NMR spectroscopy. The ^{13}C NMR spectrum shows a resonance at 172.41 ppm, attributed to the Pd-C(O)N carbon, as a doublet due to the coupling with the P nucleus of the PN ligand, confirming that **10** is a carbonylated species. The CO fixation causes the C1 and C4 *ipso* carbon resonances of the amino-phenol ring to shift downfield (153.72 ppm) and upfield (131.81 ppm), respectively, with respect to the free substrate.[11] Such shifts suggest that **10a** is a carbamoyl species, $Cl(PN)Pd\text{-}C(O)NHC_6H_4OH$, rather than a 4-aminophenoxycarbonyl complex, $Cl(PN)Pd\text{-}C(O)OC_6H_4NH_2$.[12] The $^2J_{C\text{-}Pd\text{-}P}$ value was 13.7 and indicates that **10a** presents a P-Pd-C(O)NH− *cis*-arrangement analogous to that documented by X-ray analysis for Cl(PN)Pd-C(O)O-R-OH complexes.[7] The P nucleus of the PN ligand resonates at 25.90 ppm, close to the range (22.2–24.5 ppm) found for Cl(PN)Pd-C(O)O-R-OH complexes.[7]

The proton spectra of the compounds show, in addition to the very broad resonance due to the OH group (1.5–3.0 ppm), a much less broad signal around 5 ppm attributed to the amidic proton NH. These features confirm the carbamoyl nature of the complexes. The latter signal integrates 1H and is a triplet ($J \approx$ 5 Hz) in complexes **10b**−**d** and **10f**−**h**. Such fine structure (triplet) is consistent with the coupling of the amidic proton with the methylene protons α to the N atom. In complexes **10b**−**d** and **10f**−**h** the signals of NCH_2 protons are found around 2 ppm and appear as multiplets in complexes **10f**−**h**, while are quartets in complexes **10b** and **10d**. In complex **10c** the NCH_2 protons are diastereotopic because of the presence of a chiral center and resonate as multiplets at 1.69 and 2.18 ppm. The fine structure of the latter signals has been fully elucidated by means of selective homonuclear decoupling

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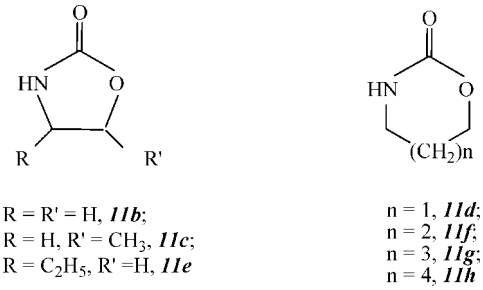
(11) The ^{13}C spectrum (100 MHz) of 4-NH_2-phenol in DMSO-d_6 shows four signals at 148.25 (C1), 140.46 (C4), 115.51 (C2), and 115.26 (C3).

(12) It is worth noting that, in 4-amido-substituted phenols, such as *para*-$HOC_6H_4NHC(O)R$ (R = H, alkyl), the C1 and C4 resonances are found respectively around 153 ppm and in the range 130–134 ppm. Conversely, upon estherification or alkoxycarbonylation of the O atom of 4-aminophenol, the resonances of both C *ipso* atoms are located around 143 ppm.

Chart 1



R = R' = H, ***11b***;
R = H, R' = CH_3, ***11c***;
R = C_2H_5, R' =H, ***11e***

n = 1, ***11d***;
n = 2, ***11f***;
n = 3, ***11g***;
n = 4, ***11h***

experiments, which have also allowed estimating the values of the $^3J_{HCNH}$ coupling constants (4 and 6.4 Hz; see Experimental Section). In complex **10e** the NH resonance (4.89 ppm, 1H) is a poorly resolved doublet because of coupling with the methyne proton, whose position has been unambiguously located by means of double resonance experiments (see Experimental Section).

All complexes **10b**−**h** exhibit a *trans*-configuration. In fact, only one resonance can be observed in their ^{31}P NMR spectra, which indicate that both phosphine ligands are equivalent, as expected for a *trans*-geometry. A *trans*-configuration was also found for the two previously described Pd-carbamoyl complexes with a secondary amino group in the amino-alcohol.[9] Accordingly, in the ^{13}C NMR spectra, the resonances of the *ipso*-, *ortho*-, and *meta*-carbons of PPh_3 ligands appear as virtual triplets, a spectroscopic feature that is usually observed in the ^{13}C spectra of *trans*-bis-phosphine Pd(II) complexes.[13] Finally, the resonance of the carbon atom of the amino-carbonyl group appears as a triplet because of coupling with the P-nuclei of the two equivalent phosphine ligands ($^2J_{C\text{-}Pd\text{-}P} \approx 5$ Hz). This signal is located around 180–184 ppm, in the same range found for the analogous Pd(II)-carbamoyl complexes of primary and secondary amines stabilized by triphenylphosphine.[5,6]

3. Reaction Mechanism and Reactivity of the Complexes

The two possible compounds that can be obtained by interaction between CO and an amino-alcohol on a metal center are shown in Scheme 3. The palladium phosphine complexes, here studied, have produced only the carbamoyl derivatives, indicating a higher nucleophilic character of the amino group, which also agrees with a recent report on the oxidative carbonylation of amino alcohols.[8]

All the synthesized complexes, as expected, by reaction with suitable promoters or upon simple heating (Scheme 4), release the amino-carbonyl moiety as cyclic carbamates **11**. Their nature is better specified in Chart 1.

Some of such cyclic molecules are very important building blocks for pharmaceutical compounds. Functionalized chiral and achiral 2-oxazolidinones (**11b**,**c**,**e**) represent a class of very important compounds, characterized by a wide range of biological activities, including antidepressant, antihistaminic, antifungal, antihypertensive, and antibacterial activities. Among them, the most representative is "linezolid", recently licensed in the USA and EU as effective against infections caused by pathogenic bacteria, methicillin- and penicillin-resistant.[14] Also, the heterocyclic six-membered 1,3-oxazinan-2-one derivatives (**11d**) exhibit a variety of biological activities, and they are being explored as anti-inflammatory agents and for treating ulcers, allergies, asthma, and diabetes.[15]

Simple 2-oxazolidinones with alkyl and phenyl group substituents in 4- and 5-positions have been stoichiometrically prepared so far using either the dangerous phosgene or phosgene-based reagents.[16] New environmentally friendly synthetic procedures are based on the reaction between 2-amino-1-alkanols with DMC or DEC.[17] Alternative procedures involving the direct carbonylation of amino alcohols under mild conditions and in a pseudocatalytic way, using a $PdCl_2$-$CuCl_2$ system,[18] or in an entirely catalytic way under mild or drastic conditions using Pd(II) salts,[9,19,20] or only under drastic conditions using the PdI_2-KI-O_2 system,[21] Pd/C-I_2-O_2[22] or salen-Co complexes,[23] have also been proposed. Recently, enantiopure 5-substituted oxazolidinones were prepared from racemic terminal epoxide and ethyl-carbamate followed by an efficient base-mediated in situ cyclization of the aminol intermediate.[24] Chiral 1,3-oxazinan-2-ones have also been recently prepared through a multistep procedure starting form optically pure 3-hydroxy-γ-butyrolactone with primary amines to give amides, which are first reduced and successively carbonylated to the desired product.[25]

In this work, the conversion of the carbamoyl ligand bonded to palladium into cyclic carbamates and/or ureas was performed exploiting the poor thermal stability of **10b**−**h** complexes in solutions (Scheme 4). In CH_3CN and in the presence of NEt_3 they decompose under nitrogen upon heating (40–60 °C), giving a red solution containing the cyclic carbamates **11b**−**h** and a precipitate formed by palladium black. Instead, when the heating was carried out in the presence of free amino-alcohol, urea was the main reaction product, which further demonstrates the carbamoyl nature of the complexes. It is likely that, upon heating, complexes **10b**−**h** undergo a reductive elimination giving chloroformamides and the Pd(0), "$Pd(PPh_3)_2$" complexes (Scheme 4). Both the compounds originated in this way are unstable: the former ones evolve to afford a cyclic carbamates or ureas (if the amino alcohol is present), the latter convert into to Pd metal and the free ligand. By carrying out the decomposition in the presence of free triphenylphosphine or under CO, the Pd(0) can be isolated as either the well-known $Pd(PPh_3)_4$ or as a mixture of Pd(0)-triphenylphosphine-carbonyl complexes

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$Pd(CO)_x(PPh_3)_{4-x}$.[26] Cyclic carbamates were also identified by IR spectra and GC-MS analysis; ureas were characterized by elemental analysis and NMR spectroscopy. The IR spectra of solutions containing the cyclic carbamates, **11b**,**c** (Chart 1) display the CO stretching at 1761–1762 cm^{-1}; for the other compounds, **11d**,**f**,**g**,**h**, the absorption appears between 1718 and 1708 cm^{-1}. Mass spectra of all compounds contain the molecular ions with a fragmentation pattern consistent with their formulation (see Experimental Section).

The reactivity of complexes **10b**−**h** with $CuCl_2$ or I_2 was also investigated. Their reaction (eqs 4, 5) were carried out in CH_3CN under nitrogen at room temperature,

$$PdCl(PPh_3)_2(CO\text{-}NH\text{-}R\text{-}OH) + 2CuCl_2 \rightarrow \mathbf{11b-h} + PdCl_2(PPh_3)_2 + 2CuCl + HCl \quad (4)$$

$$PdCl(PPh_3)_2(CO\text{-}NH\text{-}R\text{-}OH) + I_2 \rightarrow \mathbf{11b-h} + PdClX(PPh_3)_2 + HI \quad (5)$$

Unlike analogous reactions with carbamoyl complexes, prepared by carbonylation of primary and secondary amines,[5,6] or with alkoxy-carbonyl complexes obtained by carbonylation of mono-[3] or dialcohols,[7] which release the organic carbonylic function as chloroformamide or chloroformate, in the respective reactions reported above the amino-carbonyl ligand evolves quite selectively to produce the relevant cyclic carbamates. We believe that this behavior is not due to a different course of the reactions (eqs 4, 5), but to the reactivity of expected chloroformamides, "ClCONH-R-OH". The presence of the free hydroxyl group in the chain would account for the evolution of chloroformamides into the final cyclic products, probably trough a nucleophilic intramolecular attack of the OH group on the CO of the carbamoyl.

The carbamoyl complex **10a** with the aromatic amino-alcohol is much more stable. It reacts with I_2 very slowly, also upon heating (60–70 °C) (reaction 6). In this case the amino-carbonyl group is released partly as isocyanate, as the hydroxyl free group being bonded to the aromatic ring cannot interact intramolecularly with the CO moiety,

$$PdCl(CO\text{-}NH\text{-}C_6H_4\text{-}OH)(PPh_3)_2 + I_2 \rightarrow PdCl(I)(PPh_3)_2 + HI + HO\text{-}C_6H_4\text{-}N{=}C{=}O \quad (6)$$

The presence of the isocyanate moiety in the reaction mixture was evidenced by the band at 2275 cm^{-1} (ν N=C=O) in the IR spectrum of the liquid phase. This absorption disappears by adding 4-APh to the filtered solution. In this case, the expected 1,3-bis(4-hydroxyphenyl)urea, $CO(NHC_6H_4\text{-}OH)_2$, was isolated and was fully characterized by elemental analysis and its IR and NMR spectra (see Experimental Section).

The course of reactions 4 and 5 evidences a double role played by halogens or halogenated promoters. First, they promote the cleavage of the Pd−CONHROH bond and the elimination of carbamoyl moieties as chloro compounds, which then quickly convert into the cyclic carbamates, and second, they restore the palladium(II) initial species, which can be recycled.

Interestingly, the overall process of the reactions 2–4 or 2–5 is the conversion of amino-alcohols into cyclic carbamates, which is catalytic with respect to palladium and stoichiometric with respect to $CuCl_2$ or I_2 (reactions 6, 7).

$$H_2N\text{-}R\text{-}OH + CO + 2CuCl_2 \rightarrow \mathbf{11b-h} + 2HCl + 2CuCl \quad (7)$$

$$H_2N\text{-}R\text{-}OH + CO + I_2 \rightarrow \mathbf{11b-h} + 2HI \quad (8)$$

As O_2 is able to reoxidize under acidic conditions both Cu(I) and HI respectively to Cu(II) and I_2, it is possible, by using a mixture of CO/O_2, to accomplish the process in an entirely catalytic fashion and to convert under mild conditions amino-alcohols into cyclic carbamates.[27]

4. Conclusions

We report in this paper the synthesis of Pd-carbamoyl complexes of aliphatic amino alcohols bearing a primary amino group that are, to the best of our knowledge, unprecedented in the literature. Such Pd compounds, upon simple heating or by reaction under mild conditions with promoters (I_2, Cl_2, $CuCl_2$), convert selectively the amino-carbonyl group into cyclic carbamate or urea, depending on the reaction conditions, evidencing that they are the true key intermediates in the catalytic oxidative carbonylation of amino alcohols.

This study confirms that our two-step method shown in Schemes 1 and 2, able to convert stoichiometrically mono- and dialcohols, via chloroformates, into linear and cyclic carbonates, respectively, or amines into chloformamides or isocyanates, can be also applied to amino-alcohols, which are converted into cyclic carbamates or ureas. The former are compounds that find applications in the pharmaceutical industry. Therefore, the synthetic methodology described in this paper may find application for developing a simple catalytic route to the synthesis of cyclic carbamates under mild conditions avoiding toxic reagents.

5. Experimental Section

All preparations, reactions, and manipulations were carried out under the proper gas (dinitrogen or carbon monoxide) using standard vacuum-line techniques. Solvents and reactants (amino-alcohols NEt_3, $CuCl_2$, I_2) were Aldrich products and were used without further purification. The PN ligand and the relevant Pd complex, $PdCl_2(PN)$, was synthesized according to the literature.[28] The other ligands, PPh_3, 2,2′-bipyridine, 1,10-phenanthroline, and 1,2-bis-(diphenylphosphine)ethane, were Aldrich or Fluka products. Pd(II) complexes, i.e., $PdCl_2(PPh_3)_2$, $PdCl_2$(bipy), PCl_2(phen), and $PdCl_2$(dppe), were synthesized according to the literature by reacting $PdCl_2$ and the ligand in CH_3CN at 70 °C. IR spectra were recorded on a Shimadzu IR-Prestige-21 spectrophotometer. GC separations and analyses of samples, both in solution and in gas phase, were performed using a Varian Cromopack CP3800 GC connected to a Varian "Star Chromatographic Workstation". A CP Sil 8 CB 30 m, 0.53 i.d. capillary column, connected to a FID detector was used for solution analysis, whereas a 2 m, 2.0 mm i.d., Restek's Shincarbon ST packed column connected to a TCD detector was used for analysis of CO. MS spectra were obtained using a GC/MS QP5050A Shimadzu equipped with an HP-5 MS 30 m column.

NMR spectra were run on a Bruker AM 500 instrument or a Varian Inova 400 spectrometer. ^1H and ^{13}C chemical shifts are in ppm versus TMS and have been referenced to the solvent peak. ^{31}P resonances are reported in ppm and were calibrated with respect to 85% H_3PO_4.

5.1. Synthesis of Complexes. Synthesis of PdCl(PN)(CONH-C_6H_4-OH) (10a). To a suspension of $PdCl_2(PN)$ (0.405 g, 0.86mmol) in CH_3CN (20 mL), in a flask connected to a gas burette, was added

(26) Hidai, M.; Kokura, M.; Uchida, Y. *J. Organomet. Chem.* **1973**, *52*, 431–435.

(27) Giannoccaro P.; and others. Results in progress.

(28) Uhlig, E.; Keiser, Z. *Anorg. Chem.* **1974**, *406*, 1–6.

under nitrogen atmosphere 4-APhOH (0.282 g, 2.59 mmol; 4-APhOH/Pd = 3). Nitrogen was pumped off and CO was admitted at atmospheric pressure. The mixture was allowed to react under stirring at room temperature for 24 h. At this time, the color of the product in suspension turned from yellow to dark gray and the CO uptake was 20 mL (0.89 mmol), indicative that Pd complex had reacted completely. The product was filtered under nitrogen, and the residue on the filter was washed twice with a 1/1 mixture of CH_3CN/Et_2O and dried (0.406 g, 82%). Anal. Calcd (%) for $C_{26}H_{24}ClN_2O_2PPd$: Cl, 6.23; P. 5.44; Pd, 18.69. Found: Cl, 6,28, P, 5.39; Pd, 18.59. IR (Nujol): 3402 and 3273 cm^{-1} (νOH and νNH); 1606 (s), 1592 (s), 1592 (s), 1575 cm^{-1}, 1224 (s), 1154 (s) cm^{-1}. ^1H NMR (DMSO-d_6, 400 MHz, 293 K): δ 2.51 (m, 2H, $CH_{2\ (PN)}$), 3.40 (dm, 2H, $CH_{2(PN)}$, J = 28 Hz), 6.43 (d, 2H, $H_{C6H4,\beta\text{-}OH}$, J = 9 Hz), 6.82 (d, 2H, $H_{C6H4,\gamma\text{-}OH}$), 7.28–7.41 (m, 7H, $H_{P(Ph)3}$ and $H_{\beta,Py}$), 7.43 (d, 1H, $H_{\beta,Py}$, J = 7.7), 7.62–7.70 (m, 4H, $H_{P(Ph)3}$),7.85 (td, 1H, $H_{\gamma,Py}$, J = 7.7 and 1.5 Hz), 8.91 (s, 1H, NH), 9.04 (d, slightly br, 1H, $H_{\alpha',Py}$, J = 4.8 Hz). ^{13}C NMR (DMSO-d_6, 100 MHz, 293 K): δ 24.41 (d, CH_2P, J_{CP} = 29.0 Hz), 34.06 (d, CH_2Py, J_{CP} = 4.6 Hz), 122.87 and 124.86 ($C_{\beta,Py}$ atoms), 128.37 (d, $C_{meta,Ph}$, J_{CP} = 10.7 Hz), 130.39 ($C_{para,Ph}$), 132.29 (d, $C_{ipso,Ph}$, J_{CP} = 47.2 Hz), 132.78 (d, $C_{ortho,Ph}$, J_{CP} = 10.1 Hz), 139.19 ($C_{\gamma,Py}$), 151.98 ($C_{\alpha',Py}$) and 159.81 ($C_{\alpha,Py}$); 114.19 ($C_{2,OH}$), 119.44 ($C_{3,OH}$), 131.81 ($C_{4,OH}$), 153.72 ($C_{1,OH}$), 172.41 (d, C(O)O, J_{CP} = 13.7 Hz). $^{31}P\{^1H\}$ NMR (DMSO-d_6, 162 MHz, 293 K): δ 25.90.

Synthesis of *trans*-$(PPh_3)_2Pd(Cl)[C(O)NHCH_2CH_2OH]$ (10b). $PdCl_2(PPh_3)_2$ (0.300 g, 0.43 mmol) in CH_3CN (6 mL) and 2-aminoethanol (2-AE, 0.078 g, 1.28 mmol; 2-AE/Pd = 3) were allowed to react with CO at atmospheric pressure and room temperature. The mixture was reacted for 6–7 h, and upon reaction, the initial yellow suspension became white-cream. The crude product was filtered, washed with a mixture of $CH_3CN/CH_3OH/Et_2O$ (3/1/3), to remove the impurities of the salt $HO\text{-}(CH_2)_2\text{-}NH_2\cdot HCl$, and dried (0.220 g; yield 68%). The compound was purified from $CHCl_3/CH_3CN$: it was dissolved in $CHCl_3$ (4 mL), and the resulting solution was filtered, and concentrated to 2 mL. By adding CH_3CN (6 mL), pure **10b** was obtained as microcrystalline product (0.180 g, yield 55%).

Anal. Calcd (%) for $C_{39}H_{36}ClNO_2P_2Pd$: Cl, 4.70; P, 8.21 Pd, 14.10. Found: Cl, 4.81; P, 8.19; Pd, 14.02. IR (Nujol), 3577 and 3224 cm^{-1} (νOH and νNH); 1620 (s) cm^{-1} (ν C═O); 1182 (s) cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 500 MHz, 293 K): δ 1.5 (br, 1H, OH), 2.10 (q, 2H, NCH_2, J = 5.0 Hz), 2.63 (t, slightly br, 2H, CH_2OH, J = 4.5 Hz), 5.16 (t, br, 1H, NH, J = 5 Hz), 7.33–7.42 (m, 18H, H_{Ph}), 7.72–7.78 (m, 12H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 125 MHz, 293 K): δ 44.39 (NCH_2), 61.54 (CH_2OH), 128.23 (virtual t, C_{meta}, J = 4.77 Hz), 130.30 (s, C_{para}), 131.64 (virtual t, C_{ipso}, J = 22 Hz), 134.67 (virtual t, C_{ortho}, J = 6 Hz), 183.88 (t, CO, $^2J_{C\text{-}Pd\text{-}P}$ = 5 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 202 MHz, 293 K): δ 20.38.

Synthesis of 10c−h Complexes. Such complexes were prepared according to the procedure described above by reacting $PdCl_2(PPh_3)_2$ (0.300 g, 0.43 mmol) and the relevant amino alcohol in CH_3CN (6 mL) with CO at atmospheric pressure. The reaction time, the molar ratio amino-alcohol/Pd complex, and the yield, as well as the analytical and spectroscopic data (IR, NMR), are reported below.

***trans*-$(PPh_3)_2Pd(Cl)[C(O)NHCH_2CH(OH)CH_3]$ (10c).** 1-A2P/Pd complex = 3; reaction time, 20 h; yield, 54%. Anal. Calcd (%) for $C_{40}H_{38}ClNO_2P_2Pd$: Cl, 4.61; P, 8.06 Pd, 13.85. Found: Cl, 4.71; P, 7.99; Pd, 13.79. IR (Nujol), 3417 and 3350 cm^{-1} (νOH and νNH); 1606 (s) cm^{-1} (ν C═O); 1186 cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 500 MHz, 293 K): δ 0.62 (d, 3H, CH_3, $^3J_{HCCH}$ = 6.40 Hz), 1.69 (m, 1H, diastereotopic NCH_2, $^3J_{HCCH}$ = 8.9 Hz, $^3J_{HCNH}$ = 4.1 Hz), 1.2–1.6 (v br, OH), 2.18 (ddd, 1H, diastereotopic NCH_2, $^2J_{HCH}$ = 13.3 Hz, $^3J_{HCCH}$ = 2.5 Hz, $^3J_{HCNH}$ = 6.4 Hz), 2.65 (m, 1H, CH), 5.15 (poorly resolved t, br, 1H, NH, $J \approx 5$ Hz), 7.31–7.43 (m, 18H, H_{Ph}), 7.68–7.80 (m, 12H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 125 MHz, 293 K): δ 20.29 (CH_3), 49.14 (NCH_2), 66.39 (CH-OH), 128.21 (virtual t, C_{meta}, J = 4.77 Hz), 130.26 (s, C_{para}), 131.68 (virtual t, C_{ipso}, J = 22 Hz), 134.67 (virtual t, C_{ortho}, J = 6 Hz), 181.24 (t, C═O, $^2J_{C\text{-}Pd\text{-}P}$ = 5 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 202 MHz, 293 K): δ 20.30.

***trans*-$(PPh_3)_2Pd(Cl)[C(O)NHCH_2CH_2CH_2OH]$ (10d).** 3-AP/Pd = 4; reaction time, 5 h; yield, 53%. Anal. Calcd (%) for $C_{40}H_{38}ClNO_2P_2Pd$: Cl, 4.61; P, 8.06 Pd, 13.85. Found: Cl, 4.66; P, 8.02; Pd, 13.81. IR (Nujol), 3458 and 3358 cm^{-1} (νOH and νNH); 1602 (sh) and 1585 (s) cm^{-1} (ν C═O); 1186 cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 500 MHz, 293 K): δ 0.75 (quint, 2H, CH_2, J = 5.9 Hz), 1.74 (unresolved t, br, 1H, OH), 2.09 (q, 2H, NCH_2, J = 5.9 Hz), 2.89 (unresolved m, br, 2H, CH_2OH), 5.16 (t, broad, 1H, NH, J = 5.0 Hz), 7.31–7.41 (m, 18H, H_{Ph}), 7.69–7.78 (m, 13H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 125 MHz, 293 K): δ 30.98 (CH_2), 39.18 (NCH_2), 60.26 (CH_2OH), 128.17 (virtual t, C_{meta}, J = 4.77 Hz), 130.21 (s, C_{para}), 131.70 (virtual t, C_{ipso}, J = 22 Hz), 134.67 (virtual t, C_{ortho}, J = 6.67 Hz), 182.20 (t, C═O, $^2J_{C\text{-}Pd\text{-}P}$ = 5 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 202 MHz, 293 K): δ 20.11.

***trans*-$(PPh_3)_2Pd(Cl)[C(O)NH\text{-}CH(CHOH)CH_2CH_3]$ (10e).** 2-A1B/Pd = 2; reaction time, 10 h; yield, 53%. Anal. Calcd (%) for $C_{41}H_{40}ClNO_2P_2Pd$: Cl, 4.53; P, 7.91 Pd, 13.60. Found: Cl, 4.59; P, 7.86; Pd, 13.55. IR (Nujol), 3417 and 3346 cm^{-1} (νOH and νNH); 1610 (s) cm^{-1} (ν C═O); 1186 cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 400 MHz, 293 K): δ 0.41 (t, 3H, CH_3, $^3J_{HCCH}$ = 7.3 Hz), 0.51 (m, 1H, diastereotopic CH_2CH_3), 0.75 (m, 1H, diastereotopic CH_2CH_3), 2.28–2.40 (m, 2H, overlapped CH and diastereotopic CH_2OH), 2.69 (d, br, 1H, diastereotopic CH_2OH, J = 9.9 Hz), 2.74 (br, 1H, OH), 4.89 (br, 1H, NH), 7.32–7.44 (m, 18H, H_{Ph}), 7.68–7.80 (m, 12H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 100 MHz, 293 K): δ 9.71 (CH_3), 23.69 (CH_2), 51.20 (NCH), 64.21 (CH_2-OH), 128.21 (virtual t, C_{meta}, J = 5 Hz), 130.26 (s, C_{para}), 131.46 (virtual t, C_{ipso}, J = 22 Hz), 134.52 (virtual t, C_{ortho}, J = 6.1 Hz), 183.97(t, C═O, $^2J_{C\text{-}Pd\text{-}P}$ = 5 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 162 MHz, 293 K): δ 20.61.

***trans*-$(PPh_3)_2Pd(Cl)[C(O)NHCH_2CH_2CH_2CH_2OH]$ (10f).** 4-AB/Pd = 2; reaction time, 15 h; yield, 47%. Anal. Calcd (%) for $C_{41}H_{40}ClNO_2P_2Pd$: Cl, 4.53; P, 7.91 Pd, 13.60. Found: Cl, 4.59; P, 7.85; Pd, 13.53. IR (Nujol), 3385 and 3344 cm^{-1} (νOH and νNH); 1599 (s) cm^{-1} (ν C═O); 1199 cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 500 MHz, 293 K): δ 0.58 (quint, 2H, CH_2, J = 7.5 Hz), 0.98 (m, 2H, CH_2), 1.6–1.8 (br, OH), 1.98 (m, br, 2H, NCH_2, $^3J_{HCCH}$ = 7.1, $^3J_{HCNH} \approx 5$ Hz), 3.29 (t, 2H, CH_2OH, J = 6.4 Hz), 4.81 (unresolved t, br, 1H, NH), 7.31–7.43 (m, 18H, H_{Ph}), 7.68–7.80 (m, 12H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 125 MHz, 293 K): δ 24.93 (CH_2), 29.49 (CH_2), 41.43 (NCH_2), 62.13 (CH_2OH), 128.16 (virtual t, C_{meta}, J = 4.8 Hz), 130.19 (s, C_{para}), 131.73 (virtual t, C_{ipso}, J = 21.9 Hz), 134.69 (virtual t, C_{ortho}, J = 6 Hz), 181.21(t, C═O, $^2J_{C\text{-}Pd\text{-}P}$ = 5.7 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 202 MHz, 293 K): δ 20.13.

***trans*-$(PPh_3)_2Pd(Cl)[C(O)NHCH_2CH_2CH_2CH_2CH_2OH]$ (10g).** 5-APE/Pd = 2.5; reaction time, 3 h; yield 44%. Anal. Calcd (%) for $C_{42}H_{42}ClNO_2P_2Pd$: Cl, 4.45; P, 7.77 Pd, 13.36. Found: Cl, 4.51; P, 7.71; Pd, 13.31. IR (Nujol), 3360 and 3327 cm^{-1} (νOH and νNH); 1589 (s) cm^{-1} (ν C═O); 1190 cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 400 MHz, 293 K): δ 0.52 (m, 2H, NCH_2CH_2), 0.78 (quint, 2H, CH_2,$^3J_{HCCH}$ = 7.7 Hz), 1.20 (m, 2H, CH_2CH_2OH), 1.80 (v br, 1H, OH), 1.96 (m, slightly br, 2H, NCH_2, $^3J_{HCCH}$ = 7.3 Hz), 3.37 (tr, 2H, CH_2OH, $^3J_{HCCH}$ = 6.6 Hz), 4.68 (t, br, 1H, NH, $^3J_{HNCH}$ = 4.6 Hz), 7.30–7.42 (m, 18H, H_{Ph}), 7.70–7.78 (m, 12H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 100 MHz, 293 K): δ 22.69 (CH_2), 28.19 (CH_2), 31.96 (CH_2), 41.66 (NCH_2), 62.18 (CH_2OH), 128.05 (virtual t, C_{meta}, J = 5 Hz), 130.10 (s, C_{para}), 131.61 (virtual t, C_{ipso}, J = 22 Hz), 134.56 (virtual t, C_{ortho}, J = 6.1 Hz), 180.85 (t, C═O, $^2J_{C\text{-}Pd\text{-}P}$ = 6.1 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 162 MHz, 293 K): δ 20.23.

***trans*-$(PPh_3)_2Pd(Cl)[C(O)NHCH_2CH_2CH_2CH_2CH_2CH_2OH]$ (10h).** 6-AHX/Pd = 2.5); reaction time, 4 h; yield, 44%. Anal. Calcd (%) for $C_{43}H_{44}ClNO_2P_2Pd$: Cl, 4.37; P, 7.64 Pd, 13.13. Found: Cl, 4.42; P, 7.61; Pd, 13.10. IR (Nujol), 3323 and 3311 cm^{-1} (νOH

and νNH); 1597 (s) cm^{-1} (ν C═O); 1203 cm^{-1} (ν C−N). ^1H NMR ($CDCl_3$, 400 MHz, 293 K): δ 0.52 (quint, 2H, CH_2, $^3J_{HCCH}$ = 7.7 Hz), 0.74 (quint, 2H, CH_2, $^3J_{HCCH}$ = 7.7 Hz), 1.02 (quint, 2H, CH_2,$^3J_{HCCH}$ = 7.7 Hz), 1.33 (m, 2H, CH_2CH_2OH), 1.80 (v br, 1H, OH), 1.95 (m, slightly br, 2H, NCH_2, $^3J_{HCCH}$ = 7.7 Hz), 3.47 (tr, 2H, CH_2OH, $^3J_{HCCH}$ = 6.6 Hz), 4.62 (t, br, 1H, NH, $^3J_{HNCH}$ = 4.6 Hz), 7.30–7.42 (m, 18H, H_{Ph}), 7.70–7.78 (m, 12H, H_{Ph}). ^{13}C NMR ($CDCl_3$, 100 MHz, 293 K): δ 25.21 (CH_2), 26.30 (CH_2), 28.40 (CH_2), 32.27 (CH_2), 41.71 (NCH_2), 62.47 (CH_2OH), 128.08 (virtual t, C_{meta}, J = 4.6 Hz), 130.13 (s, C_{para}), 131.66 (virtual t, C_{ipso}, J = 22 Hz), 134.58 (virtual t, C_{ortho}, J = 6.1 Hz), 180.79 (t, C═O, $^2J_{C\text{-}Pd\text{-}P}$ = 5 Hz). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 162 MHz, 293 K): δ 20.18.

5.2. Decomposition of Complexes with HCl and Analysis of CO. A weighted amount of the complex was reacted with an excess of a 2 M HCl methanol solution in an inverted Y-shaped glass reactor connected to a gas burette. The CO evolved was measured at ambient temperature and pressure and analyzed by GC. In a typical experiment the complex **10d** (0.140 g, 0.182 mmol) in CH_3CN (2 mL) and the HCl solution (2 mL) were separately charged, under dinitrogen, into the two arms of the glass reactor. After mixing, the gas evolved was measured: 4.2 mL (0.19 mmol) of CO at 22 °C and 0.1 MPa were obtained.

The decomposition of other complexes was performed according to the above-described procedure. In Table 1 are indicated the analytical data for some complexes.

5.3. Thermal Decomposition of Complexes and Conversion of the Carbamoyl Ligands into the Cyclic Carbamates and /or Ureas. 5.3.1 Conversion of the Carbamoyl Ligands into the Cyclic Carbamates. Complex **10b** (0.42 mmol) in 6 mL of a mixture of CH_3CN/NEt_3 (6/1) was heated at 60 °C for 3 h, under dinitrogen. The IR spectrum of the resulting reaction solution displayed a band at 1762 cm^{-1} attributed to the five-membered cyclic carbamate 2-oxazolidin-2-one (**11b**). The carbamate in solution was also confirmed by GC-MS spectrum. MS (*m*/*z*) (relative intensity %): 87 (M^+, 80), 82 (61), 59 (56), 42 (60), 29 (100). The carbamate was separated from the reaction mixture by adding PPh_3 (0.84 mmol; PPh_3/Pd = 2), which caused the precipitation of $Pd(PPh_3)_4$, recognized by comparison of its IR spectrum with that of an authentic sample. The filtered solution was evaporated to dryness, and from the residue, pure **11b** was extracted as a solid product with diethyl ether and analyzed. Anal. Calcd (%) for $C_3H_5NO_2$: C, 41.38; H, 5.79; N, 16.09. Found: C, 41.27; H, 5.72; N, 16.01.

The decomposition of the **10c**−**f** complexes was carried out in the same way. The relevant carbamates were identified in solution by IR spectrum and further characterized by elemental and GC-MS analysis. Cyclic carbamates **11g**−**h** formed in the decomposition of **10g**−**h** were identified only by IR and GC-MS spectra. Details are reported below (Section 5.3.2).

Decomposition of Complex 10c. Complex **10c** (0.31mmol) in 4 mL of a mixture of CH_3CN/NEt_3 (6/1) was heated at 60 °C for 3 h. The IR spectrum of the reaction solution displayed a band at 1761 cm^{-1} due to the formation of 5-methyl-2-oxazolidin-2-one (five-membered cyclic carbamate, **11c**). GC-MS (*m*/*z*) (relative intensity %): 101 (M^+, 76), 86 ((15), 73 (18), 56 (22), 45 (100), 42 (23), 29 (75). The pure carbamate was separated from the reaction mixture as described above and analyzed. Anal. Calcd (%) for $C_4H_7NO_2$: C, 47.52; H, 6.98; N, 13.85. Found: C, 47.39; H, 6.93; N, 13.80.

Decomposition of Complex 10d. Complex **10d** (0.33 mmol) in 4 mL of a mixture of CH_3CN/NEt_3 (6/1) was heated at 60 °C for 3 h. The IR spectrum displayed in solution a band at 1708 cm^{-1}, due to the formation of 1,3-oxazinan-2-one (six-membered cyclic carbamate **11d**). GC-MS (*m*/*z*) (relative intensity %): 101 (M^+, 100%), 71 (14%), 56 (79%), 44 (20%), 43 (18%), 42 (18%), 41 (16%), 29 (78%). The carbamate was separated from the reaction mixture as described above and analyzed. Anal. Calcd (%) for $C_4H_7NO_2$: C, 47.52; H, 6.98; N, 13.85. Found: C, 47.41; H, 6.94; N, 13.79.

Decomposition of Complex 10e. Complex **10e** (0.35 mmol) in 4 mL of a mixture of CH_3CN/NEt_3 (6/1) was heated at 60 °C for 4 h. The IR spectrum of the reaction solution displayed a band at 1762 cm^{-1} due to the formation of 4-ethyl-2-oxazolidin-2-one (five-membered cyclic carbamate **11e**). GC-MS (*m*/*z*) (relative intensity %): 115 (M^+, 10), 86 (89), 73(10), 58 (36), 42 (100). The carbamate was separated from the reaction mixture as described above and analyzed. Anal. Calcd (%) for $C_5H_9NO_2$: C, 52.16; H, 7.88; N, 12.16; Found: C, 52.02; H, 7.84; N, 12.12.

Decomposition of Complex 10f. Complex **10f** (0.40 mmol) in 4 mL of a mixture of CH_3CN/NEt_3 (6/1) was heated at 60 °C for 4 h. The IR spectrum of the reaction solution displayed a band at 1715 cm^{-1} due to the formation of 1-oxa-3-aza-cycloheptan-2-one (seven-membered cyclic carbamate **11f**). GC-MS (*m*/*z*) (relative intensity %): 115 (M^+, 55), 86 (31), 56 (33), 43 (45), 42 (100), 41 (49), 29 (43). The pure carbamate was separated from the reaction mixture as described above and analyzed. Anal. Calcd (%) for $C_5H_9NO_2$: C, 52.16; H, 7.88; N, 12.16. Found: C, 52.03; H, 7.82; N, 12.11.

5.3.2. Conversion of the Carbamoyl Ligands into Symmetrical *N*,*N*′-Hydroxydialkyl Ureas. The conversion was performed only with complexes **10d**,**f**,**g**,**h** bearing the amine and alcohol functionalities in a nonvicinal position.

Decomposition of Complex 10d in the Presence of 3-Amino-1-propanol. To a suspension of complex **10d** (0.66 mmol) in CH_3CN (4 mL) were added NEt_3 (0.5 mL) and 3-AP (0.100 g, 1,33 mmol; 3-AP/Pd = 2) under dinitrogen. The mixture was heated to 60 °C and allowed to react for 2 h. The IR spectrum of the reaction solution displayed a weak band at 1708 cm^{-1} and a more intense band at 1643 cm^{-1}, due to the urea, $CO[NH\text{-}(CH_2)_3\text{-}OH]_2$ (**12d**). The solution, exposed to CO gas, showed the appearance of a new band at 1853 cm^{-1}, indicative of the presence in solution of a Pd(0)-carbonyl-phosphine complex.[26] The pure urea **12d** was extracted from the reaction mixture, removing by filtration the Pd, as $Pd(PPh_3)_4$, and evaporating to dryness the filtered solution. The residue, constituted of **12d** and $NEt_3 \cdot HCl$, was suspended in CH_3CN and neutralized with NaOH. The resulting mixture was heated to 50 °C and filtered, and after cooling, 1,3-bis(3-hydroxypropyl)urea (**12d**) was precipitated as a white crystalline product, which was characterized by elemental analysis, IR, and NMR. Anal. Calcd (%) for $C_7H_{16}N_2O_3$: C, 47.71; H, 9.15; N, 15.89. Found: C, 47.60; H, 9.11; N, 15.84. IR (DMSO): ν(OH, NH) = 3420 cm^{-1} (br); ν(CO) = 1662.6 cm^{-1}. IR (Nujol), ν(OH, NH) = 3342 (sh), 3304 (br) cm^{-1}; ν(CO) = 1620 (br). ^1H NMR (CD_3OD, 600 MHz, 293 K): δ 1.68 ppm (quint, 4H, $-CH_2CH_2CH_2-$, $J_{H\text{-}H}$ = 6.4 Hz), 3.21 ppm (t, 4H, $-NCH_2-$, $J_{H\text{-}H}$ = 6.5 Hz), 3.59 ppm (t, 4H, $-OCH_2-$, $J_{H\text{-}H}$ = 6.7 Hz). ^{13}C NMR (CD_3OD, 600 MHz, 293 K): 32.68 ($-CH_2-$), 36.54 ppm ($-NCH_2-$), 59.02 ppm ($-CH_2OH$), 160.20 ppm ($-C(O)-$).

Decomposition of Complex 10f in the Presence of 4-Amino-1-butanol. The reaction was carried out as above. Thus, **10f** (0.52 mmol), 4-AB (1.1 mmol), and PPh_3 (1.09 mmol; PPh_3/Pd = 2) were suspended in 6 mL of a mixture of CH_3CN/NEt_3 (8/1) and heated at 60 °C for 3 h. The $Pd(PPh_3)_4$ formed in the reaction was removed by filtration, and the IR spectrum of the solution showed the presence of a very weak band at 1716 cm^{-1} and a more intense band at 1640 cm^{-1} due to the 1,3-bis(4-hydroxybutyl)urea (**12f**). The solution was evaporated to dryness and **12f** was extracted from the solid residue according to the procedure described above and characterized. Anal. Calcd (%) for $C_9H_{20}N_2O_3$: C, 52.92; H, 9.87; N, 13.71. Found: C, 52.80; H, 9.84; N, 13.66. IR (DMSO), ν(OH, NH) = 3466 (sh), 3307 (br) cm^{-1}; ν(CO) = 1666.5 cm^{-1}. IR (Nujol), ν(OH, NH) = 3380 (sh), 3325 cm^{-1}; ν(CO) = 1620, 1574 cm^{-1}. ^1H NMR (CD_3OD, 600 MHz, 293 K): δ 1.68 ppm (m, 8H, $-CH_2CH_2CH_2CH_2$), 3.21 ppm (t, 4H, $-NCH_2-$, $J_{H\text{-}H}$ = 6.5 Hz), 3.59 ppm (t, 4H, $-OCH_2-$, $J_{H\text{-}H}$ = 6.3 Hz). ^{13}C NMR (CD_3OD, 600 MHz, 293 K): 26.43 ppm ($-NCH_2CH_2-$), 29.48 ppm

(−*C*H$_2$CH$_2$OH), 39.42 ppm (−N*C*H$_2$−), 61.24 ppm (−*C*H$_2$OH), 159.98 ppm (−*C*(O)−).

Decomposition of Complex 10g. Complex **10g** (0.30 mmol) and PPh_3 (0.158 g, 0.60 mmol; PPh_3/Pd = 2) in 5 mL of a mixture of CH_3CN/NEt_3 (6/1) were heated at 60 °C for 12 h. The $Pd(PPh_3)_4$ formed was removed, and the IR spectrum of the filtered solution showed bands at 1722 (m) and 1676 (w) cm^{-1}. The latter disappeared by adding 5-aminopentanol, which caused the precipitation of a white-gray product, which was collected and characterized as 1,3-bis(5-hydroxypentyl)urea (**12g**) by elemental analysis and IR and NMR spectra. Anal. Calcd (%) for $C_{11}H_{24}N_2O_3$: C, 56.87; H, 10.41; N, 12.05. Found: C, 56.74; H, 10.38; N, 12.02. IR (DMSO): ν(CO) = 1666.5 cm^{-1}. IR (Nujol): ν(OH, NH) = 3395 (sh), 3331 (br) cm^{-1}; ν(CO), 1614 (s), 1589 (s) cm^{-1}. ^{1}H NMR (CD_3OD, 600 MHz, 293 K): 1.30 ppm (m, 4H, −CH$_2$C*H*$_2$CH$_2$−), 1.40 ppm (quint, 4H, −NCH$_2$C*H*$_2$−, $J_{H\text{-}H}$ = 7.1 Hz), 1.46 ppm (quint, 4H, -C*H*$_2$CH$_2$O-, 6.7 Hz), 3.02 ppm (t, 4H, −NC*H*$_2$− $J_{H\text{-}H}$ = 7 Hz), 3.46 ppm (t, 4H, −OC*H*$_2$−, $J_{H\text{-}H}$ = 6.5 Hz). ^{13}C NMR (CD_3OD, 600 MHz, 293 K): 21.30 ppm (−CH$_2$*C*H$_2$CH$_2$−), 28.26 ppm (−NCH$_2$*C*H$_2$−), 30.42 ppm (−*C*H$_2$CH$_2$OH), 38.05 ppm (−N*C*H$_2$−), 59.93 ppm (−*C*H$_2$OH), 158.44 ppm (−*C*(O)−).

On the basis of these results, the band at 1676 cm^{-1} was attributed to the chloroformate Cl-CO(NH(CH$_2$)$_5$-OH) produced from **10g** by reductive elimination. The filtered solution after the removal of the urea still showed the band at 1722 cm^{-1}, which was assigned to the cyclic carbamate 1-oxa-3-aza-cycloctan-2-one (**11g**), as confirmed by its GC-mass spectrum. MS (*m*/*z*) (relative intensity %): 129 (M$^+$, 70), 101 (18), 86 (100), 72(10), 58 (15) 41(60), 29 (31).

Decomposition of Complex 10h. Complex **10h** (0.28 mmol) and PPh_3 (0.147 g, 0.56 mmol; PPh_3/Pd = 2) in 5 mL of a mixture of CH_3CN/NEt_3 (6/1) were heated at 60 °C for 12 h. The original pink-cream suspension turned to yellow, and $Pd(PPh_3)_4$ was removed by filtration. The IR spectrum of the filtered solution displayed bands at 1724 (w) and 1675 (m) cm^{-1}. The latter disappeared by adding 6-aminohexanol, which caused the precipitation of a white-gray product, which was collected by filtration and characterized as 1,3-bis(6-hydroxyhexyl)urea (**12h**) by elemental analysis and IR and NMR spectra. Anal. Calcd (%) for $C_{13}H_{28}N_2O_3$: C, 59.97; H, 10.84; N, 10.75. Found: C, 59.83; H, 10.81; N, 10.71. IR (DMSO): ν(CO) = 1666 cm^{-1}. IR (Nujol): ν(OH, NH) = 3394, 3331 cm^{-1}; ν(CO) = 1614 (s), 1574 (S) cm^{-1}. ^{1}H NMR (CD_3OD, 600 MHz, 293 K): δ 1.37 ppm (m, 8H, −CH$_2$C*H*$_2$C*H*$_2$CH$_2$−), 1.49 ppm (quint, 4H, −NCH$_2$C*H*$_2$−, $J_{H\text{-}H}$ = 7.1 Hz), 1.54 ppm (quint, 4H, −C*H*$_2$CH$_2$O−, $J_{H\text{-}H}$ = 7 Hz), 3.11 ppm (t, 4H, −NC*H*$_2$; $J_{H\text{-}H}$ = 7 Hz), 3.55 ppm (t, 4H, −OC*H*$_2$−, $J_{H\text{-}H}$ = 6.5 Hz). ^{13}C NMR (CD_3OD, 600 MHz, 293 K): 25.27 ppm (−NCH$_2$CH$_2$*C*H$_2$−), 26.35 ppm (−*C*H$_2$CH$_2$CH$_2$OH, 29.96 ppm (−NCH$_2$*C*H$_2$−), 32.20 ppm (−*C*H$_2$CH$_2$OH), 39.54 ppm (−N*C*H$_2$−), 61.48 ppm (−*C*H$_2$OH), 159.95 ppm (−*C*(O)−).

The filtered solution after the removal of the urea still showed the band at 1722 cm^{-1}, which was assigned to the cyclic carbamate 1-oxa-3-aza-cyclonona-2-one (**11h**), as confirmed by its mass spectrum. MS (*m*/*z*) (relative intensity %): 143 (M$^+$, 15), 142 (20), 115 (18), 86 (100), 84 (15), 58 (40), 44 (65), 42 (100), 41 (38), 30 (60), 29 (36).

5.4. Decomposition of Complexes with I_2. All the reactions were carried out in the inverted Y-shaped glass reactor described above.

Reaction of 10a Complex with I_2. Complex **10a** (0.140 g, 0.24 mmol) in 2 mL of hexane and I_2 (0.060 g, 0.24 mmol; I_2/Pd = 1) in 2 mL of hexane were charged into the two branches of the reactor. The red-violet iodine solution was added to the suspension of the complex, and the resulting mixture was heated to 60 °C and allowed to react under stirring until its color became brown (∼4 h). The mixture was filtered and the resulting red-brown solution showed a band a 2275 cm^{-1}, indicative of the presence of the isocyanate OH-C$_6$H$_4$-N=C=O. The latter was characterized as the relevant urea derivative by reacting the solution at 50 °C for 2 h with 4-APhOH (0.031 g, 0.29 mmol). After removal of the solvent, the resulting brown semisolid product was reacted with NaOH to neutralize HI, then was washed in succession with H_2O and CH_3CN/Et_2O (1/4) and extracted with methanol (4 mL). The resulting red solution was filtered and concentrated almost to dryness, and by adding Et_2O, a white product was obtained. It was characterized as the urea 1,3-bis(4-hydroxyphenyl)urea by elemental analysis and IR and NMR spectra. Anal. Calcd (%) for $C_{13}H_{12}N_2O_3$: C, 63.93; H, 4.96; N, 11.46. Found: C, 63.79; H, 4.93; N, 11.43. The IR spectrum showed bands at 3306 (s, br) and at 1643 cm^{-1} (s; νCO). ^{1}H NMR (CD_3OD, 500 MHz, 293 K): 6.72 ppm (m, 4H, H3), 7.16 (m, 4H, H2). ^{13}C NMR (CD_3OD, 125 MHz, 293 K): 116.32(C3), 123.38(C2), 132.14(C1), 154.63(C4), 156.78(C=O) ppm.

The residual solid of filtration was characterized as PdClI(PN). Anal. Calcd (%) for $C_{19}H_{18}ClINPPd$: Pd, 19.00; P, 5.53; Cl, 6.33; I, 22.66. Found: Pd, 18.94; P, 5.49; Cl, 6.26; I, 22.70.

Reaction of Complex 10d with I_2. Complex **10d** (0.150 g, 0.195 mmol) in 2 mL of hexane and I_2 (0.050 g, 0.195 mmol) in 2 mL of hexane were charged into the two branches of the reactor and reacted as above. The mixture was filtered, and the brown residue and solution were analyzed. The IR spectrum of the solution showed an intense band at 1708 cm^{-1}, attributed to the six-membered cyclic carbamate 1,3-oxazinan-2-one (**11d**). The compound was also identified through the GC-MS spectrum, which was identical with that reported above. The brown residue analyzed as $PdICl(PPh_3)_2$. Anal. Calcd (%) for $C_{36}H_{30}ClIP_2Pd$: Pd, 13.42; P, 7.82; Cl, 4.47; I, 16.00. Found: Pd, 13.37; P, 7.79; Cl, 4.38; I, 16.18.

The reaction of the other complexes was carried out according to the same procedure. Complexes **10b**,**c**,**e**,**f** reacted with I_2 and converted the amino-carbonyl moiety into the relevant cyclic carbamate. The IR spectra of the reaction solutions showed bands at 1762, 1761, 1762, and 1715 cm^{-1} respectively attributed to the cyclic carbamates **11b**,**c**,**e**,**f**. The compounds were identified also by their GC-MS spectra, which were identical to those reported above. Complexes **10g**,**h** by reaction with I_2 gave a mixture of two carbonylic organic products evidenced by IR spectra that showed the presence of two bands at 1724 and 1676 cm^{-1}. This behavior is similar to that observed upon thermal decomposition of the two complexes. The mixture was filtered, and by addition of relevant amino carbonyl ligand 5-APE (**g**) and 6-AHX (**h**), the band at 1676 disappeared. The reaction solution was evaporated to dryness and the solid residue partially dissolved in CH_3CN. The IR spectrum of the CH_3CN solution showed the band at 1724, which was attributed to the cyclic carbamates **11g**,**h** on the basis of their mass spectrum. The white residue was characterized as urea (**12g**,**h**) by IR and NMR spectra, which were identical with those reported above.

5.5. Reaction of Complexes 10b−f with $CuCl_2$. All the reactions were performed in the above-described inverted Y-shaped glass reactor. In a typical experiment, complex **10b** (0.22 mmol) in CH_3CN (2 mL), and dry $CuCl_2$ (0.44 mmol) in CH_3CN (3 mL) were separately charged into the two branches of the glass reactor. The reactants were mixed, and the resulting liquid and solid of reaction were analyzed. The IR spectrum of the solution showed a band at 1762 cm^{-1}, due to the five-membered cyclic carbamates **11b**, confirmed also by its MS spectrum, which was identical to that reported reported above. The solid was analyzed as a mixture of $PdCl_2(PPh_3)_2$ and CuCl as previously reported.[4]

The reactions of the other complexes **10c−f** were carried out according to the above-described procedure. The relevant cyclic

carbamates **11c−f** were recognized by IR and MS spectra, which were identical with those reported above.

The reaction of complexes **10g**,**h** did not yield selectively the relevant cyclic carbamates **11g**,**h**. The IR spectra of their reaction solutions displayed two bands centered at 1724 and 1676 cm^{-1}, indicative of the formation of cyclic carbamate and chloroformate: the former was identified by MS spectrum, the latter by its urea derivative. A similar behavior was found upon both thermal decomposition of the complex and reaction with iodine.

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