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Comparison of palladium carbene and palladium phosphine catalysts for catalytic coupling reactions of aryl halides

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Abstract

Palladium-catalyzed C–C and C–N bond forming reactions of aryl halides continue to be a major focus in catalysis research for the fine chemical industry. Still there exists a significant need for the development of more active and productive palladium catalysts. Although an increasing number of new catalysts is reported, it is often difficult to compare them. Here, we present a more detailed comparison of the catalytic performance of different monocarbenepalladium(0) complexes and various so-called in situ palladium phosphine and carbene catalysts in Suzuki, Kumada, and Buchwald–Hartwig amination reactions. Depending on the type of coupling reaction good to excellent yields of the desired products are obtained in the presence of both carbene- and phosphine-based catalysts. In general, phosphine-based catalysts appear to be more efficient for amination and Suzuki reactions of aryl chlorides. On the other hand, the carbene-based palladium catalysts work well in Kumada couplings of various aryl chlorides.

Keywords: Aryl halides; Carbene ligands; Homogeneous catalysis; Palladium; Phosphine ligands

1. Introduction

More than 80% of all current pharmaceuticals contain aromatic or heteroaromatic units as integral part of their structure [1]. It is estimated that a similar amount of agrochemicals possess aryl or heteroaryl groups. Therefore, the refinement of aryl halides is of major importance for the synthesis of organic building blocks and new active agents. Due to their generality especially palladium-catalyzed coupling reactions of aryl–X derivatives, such as the Suzuki [2–4], Heck [5,6], and Kumada reaction [7], as well as the Buchwald–Hartwig amination [8] offer opportunities for the synthesis of substituted arenes. Interestingly, applying these reactions an environmentally more friendly production of pharmaceuticals and agrochemicals is often possible due to the minimization of steps compared to classical organic syntheses. Advantageously, the starting materials are readily available and the palladium catalysts show a broad tolerance towards various functional groups.

Despite these advantages until recently relatively few industrial applications have been realized [9–11]. This may be explained partly by the low catalyst efficiency in a number of interesting coupling reactions. Often comparably large amounts (>5 mol%) of a certain palladium pre-catalyst have to be used in order to obtain optimal yields in these reactions. Hence, catalyst costs dominate raw material costs. Furthermore, it is more difficult in these cases to keep the palladium content below 1 ppm in pharmaceutical and agrochemical end products. Although examples of highly productive palladium catalysts for coupling reactions are known [12–27], the development of new catalysts is an actual goal in organometallic chemistry and homogeneous catalysis. In addition to phosphine-based catalysts in the last 5 years heterogeneous catalysts [28] and especially palladium carbene complexes have evolved as new catalysts for Heck [29], Suzuki [30,31], and Sonogashira coupling reactions [32], and amination of aryl halides [31,33].

Critical for the catalyst activity in the above-mentioned coupling reactions is the easy formation of low-coordinated

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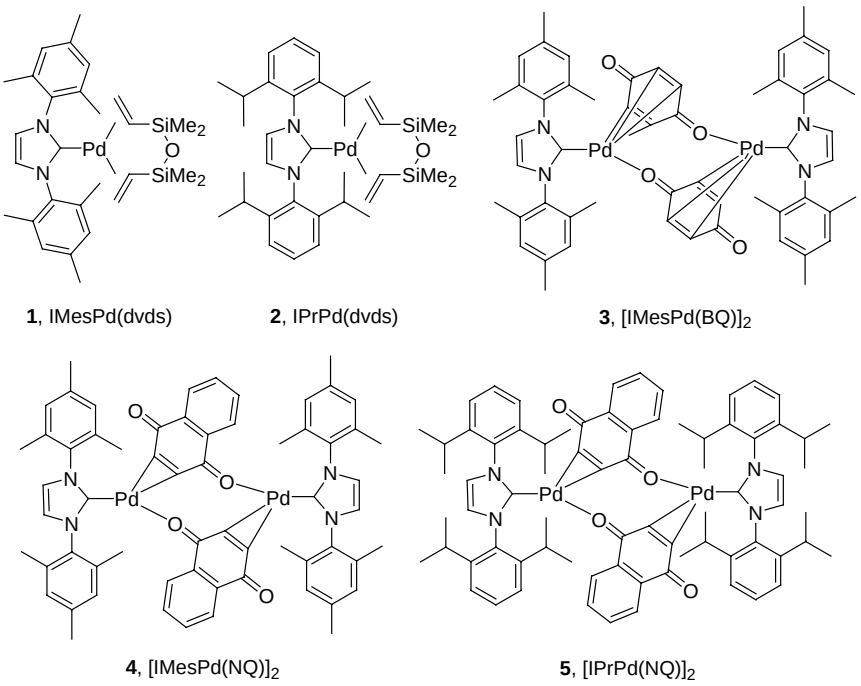


Fig. 1. Stable monocarbenepalladium(0) complexes.

palladium(0) complexes under reaction conditions. At best a palladium(0) pre-catalyst should be used, which generates a defined low-coordinated $14e^-$ or $16e^-$ palladium complex at low temperature (<50 °C). Thus, we [34] and others [35–39] have studied palladium-catalyzed coupling reactions of aryl halides in the presence of defined low-coordinated palladium phosphine complexes. These catalysts show often higher activity under milder conditions compared to so-called in situ palladium catalysts, which consist of mixtures of Pd(0) or Pd(II) compounds and strongly binding phosphine or carbene ligands. Examples of defined stable monocarbenepalladium(0) complexes (**1**–**5**) which have been developed recently by us are shown in Fig. 1 [40].

Here, as additional stabilizing ligand 1,1,3,3-tetramethyl-1,3-divinyldisiloxane (dvds), benzoquinone (BQ) or naphthoquinone (NQ) are used. These complexes have been demonstrated to be suitable catalysts for coupling reactions of aryldiazonium salts [40], aryl chlorides [41], and telomerization reactions [13,42]. In order to further explore the catalytic potential of this class of catalysts, we became interested in a comparison of these complexes with state-of-the-art in situ palladium phosphine and palladium carbene catalysts for different C–C and C–N coupling reactions. Despite the interest in palladium carbene and palladium phosphine catalysts so far no detailed comparison of these catalysts for different coupling processes has been described.

Thus, in this paper we report on the use of defined monocarbenepalladium(0) complexes in Suzuki, Kumada, and Buchwald–Hartwig amination reactions of aryl halides. For the first time a direct comparison of the catalyst performance with different in situ palladium phosphine and carbene catalysts for these three important coupling reactions is shown.

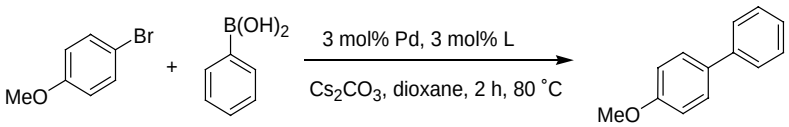
2. Results and discussion

2.1. Suzuki reactions of aryl halides

The cross-coupling reaction of aryl halides and arylboronic acids (Suzuki reaction) is the most versatile and important method for the synthesis of substituted biaryls. This class of compounds constitutes important building blocks for the synthesis of biologically active substances, e.g. pharmaceuticals, such as the sartan family of drugs for high blood pressure [43,44] and herbicides [45]. Additionally, biaryls have found application as chiral ligands for catalysis [46] and in material science, e.g. as liquid crystals [47].

Recently, Suzuki cross-coupling reactions of aryl chlorides catalyzed by different palladium/phosphine systems have been extensively studied in organic synthesis due to the economically attractive nature of the starting materials [48]. Notable advancements using carbenes as ligands for this reaction have been reported especially by Nolan and co-workers [31,49,50].

Although most of our catalytic studies focused on aryl chlorides as substrates (see below), we started our investigation with the coupling of 4-bromoanisole (a deactivated bromoarene) and phenylboronic acid (Scheme 1). Table 1 summarizes the results obtained in the presence of **1**, **2**, **4**, and **5** and different in situ catalyst systems. The isolated Pd(0) carbene complexes **1**, **2**, **4**, and **5** show results (Table 1, entries 1, 2, 4, 5) similar to those of the corresponding in situ $Pd(OAc)_2$/ligand systems (Table 1, entries 7, 8; 63–76% yield). Due to the relatively easy oxidative addition step (in comparison to aryl chlorides) even without ligand, with simple $Pd(OAc)_2$, 4-methoxybiphenyl is obtained in 54%



Scheme 1. Suzuki coupling of 4-bromoanisole and phenylboronic acid.

Table 1
Suzuki coupling of 4-bromoanisole and phenylboronic acid

Entry	Catalyst	Conversion (%)[a]	Yield (%)[a]
1	IMesPd(dvds) (**1**)	92	65
2	IPrPd(dvds) (**2**)	90	71
3	IPrPd(dvds) (**2**)/NQ	28	11
4	**[IMesPd(NQ)]$_2$ (4)**	**81**	**76**
5	[IPrPd(NQ)]$_2$ (**5**)	77	63
6	[IPrPd(NQ)]$_2$ (**5**)/dvds	40	2
7	Pd(OAc)$_2$/IPrHCl	88	73
8	Pd(OAc)$_2$/IMesHCl	80	70
9	Pd(OAc)$_2$	62	54
10	Pd(dvds)[b]/IMesHCl	5	<1
11	Pd(dvds)[b]	8	<1
12	**Pd(OAc)$_2$/BuPAd$_2$**	**100**	**99**
13	**Pd(OAc)$_2$/*o*-biph-PCy$_2$**	**99**	**85**
14	**Pd(OAc)$_2$/P*t*Bu$_3$**	**100**	**99**

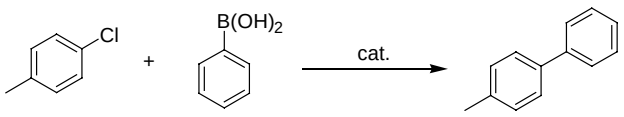
Reaction conditions: 2 mmol 4-bromoanisole, 3 mmol phenylboronic acid, 4 mmol Cs_2CO_3, 6 ml dioxane, 3 mol% [Pd], 3 mol% ligand (precursor), 80 °C, 2 h.

[a] Conversion and yield were determined by GC using an internal standard (diethyleneglycol di-*n*-butylether).

[b] Solution of Pd(0) in dvds (ca. 8 wt.% Pd).

yield (Table 1, entry 9). In contrast, in the presence of additional olefinic ligands (Table 1, entries 3, 6) or by using Pd(dvds) solution (Table 1, entries 10, 11) the catalyst activity breaks down, regardless of the presence of carbene ligand. This observation indicates a strong binding of the olefinic groups to the palladium center, thereby blocking the required free coordination sites. In addition, the olefin reduces the electron density on the Pd center by backdonation from the metal to the olefin, which decreases the activity for oxidative addition into the C–Br bond. Interestingly, an increase in the catalyst productivity is observed upon changing from a carbene-based to a phosphine-based catalyst system. Thus, sterically hindered basic phosphine ligands, such as BuPAd$_2$, *o*-biph-PCy$_2$, and P*t*Bu$_3$ led to improved yields of 4-methoxybiphenyl (Table 1, entries 12–14; 81–99% yield).

Next, the Suzuki reaction of 4-chlorotoluene and phenylboronic acid was studied in more detail (Scheme 2). In addition to the variation of catalysts, also solvents (toluene, dioxane), ligands (PCy$_3$, P*t*Bu$_3$, IMes, IPr) and bases



Scheme 2. Suzuki coupling of 4-chlorotoluene and phenylboronic acid.

(K_3PO_4, $K_3PO_4 \cdot H_2O$, KO*t*Bu, Cs_2CO_3) have been changed and tested at different reaction temperatures (80–100 °C) and reaction times (2–20 h).

This optimization study revealed that best results are obtained in the presence of Pd(II)/phosphine systems. Here, Pd(OAc)$_2$/P*t*Bu$_3$ (0.1 mol%) or Pd(OAc)$_2$/BuPAd$_2$ (0.1 mol%) with K_3PO_4 as the base gave yields >90% of 4-methylbiphenyl at 100 °C after 20 h. Using 1,3-dimesitylimidazol-2-ylidene (IMes) as carbene ligand 4-methylbiphenyl was found in 51% yield (Cs_2CO_3, dioxane, 3 mol% Pd(OAc)$_2$/IMes, 80 °C, 2 h). Surprisingly, the reproducibility of the same reaction in the presence of IMesHCl was very low.

Fig. 2 shows the results of the Suzuki reaction of 3-chloropyridine, 4-chlorotoluene, 4-chloroanisole, and 1-chloro-2-fluorobenzene with phenylboronic acid. Here, we compared different catalysts applying the conditions, which have been optimized for the Pd(OAc)$_2$/IMes system. In general, three sets of catalyst systems (Fig. 2 from left to right: monocarbenepalladium(0) complexes, in situ Pd(II)/carbene, and in situ Pd(II)/phosphine) were tested under the same conditions. While the dvds-derived monocarbenepalladium(0) complexes exhibited only very low activity, the quinone-bridged palladium catalyst precursors gave moderate yields with non-activated and deactivated aryl chlorides and good yields with slightly activated 1-chloro-2-fluorobenzene. The results depicted in Fig. 2 clearly demonstrate the significantly higher productivity of the carbenepalladium(NQ) complexes compared to the carbenepalladium(dvds) complexes.

As reference systems, phospine-based in situ systems (BuPAd$_2$, *o*-biph-PCy$_2$, P*t*Bu$_3$) were also tested. It is important to note that in general in Suzuki reactions the palladium phosphine catalyst systems can be applied at 1–2 orders of magnitude lower concentration compared to the palladium carbene catalysts (but generally with a phosphine/palladium ratio of 2:1). Thus, palladium/phosphine catalysts seem to be more suited for this reaction.

2.2. Kumada coupling of aryl chlorides

A more direct route to biphenyls compared to the Suzuki reaction is the palladium-catalyzed coupling of aryl halides with aryl *Grignard* reagents (Kumada reaction) [7]. Here, the additional step for preparation of the "intermediate" boronic acid derivatives is not required (Scheme 3). However, the application of Grignard reagents instead of boronic acids results in some disadvantages: Grignard compounds are not stable to moisture and air, and cannot be stored for a long

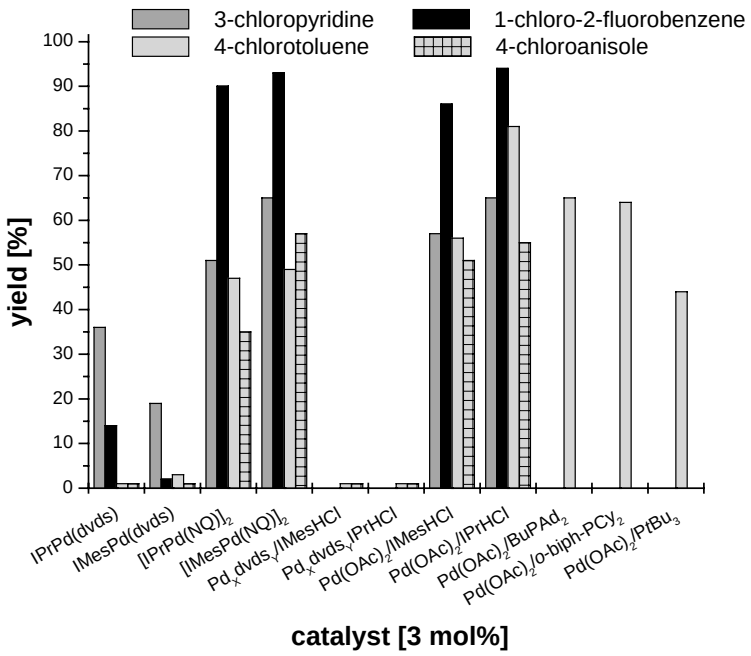


Fig. 2. Screening of catalysts and substrates in the Suzuki coupling of aryl chlorides with phenylboronic acid. Reaction conditions: 2 mmol chloroarene, 3 mmol phenylboronic acid, 4 mmol Cs_2CO_3, 6 ml dioxane, 3 mol% [Pd], 3 mol% ligand, 80 °C, 2 h. Yields were determined by GC using diethyleneglycol di-*n*-butylether as internal standard.

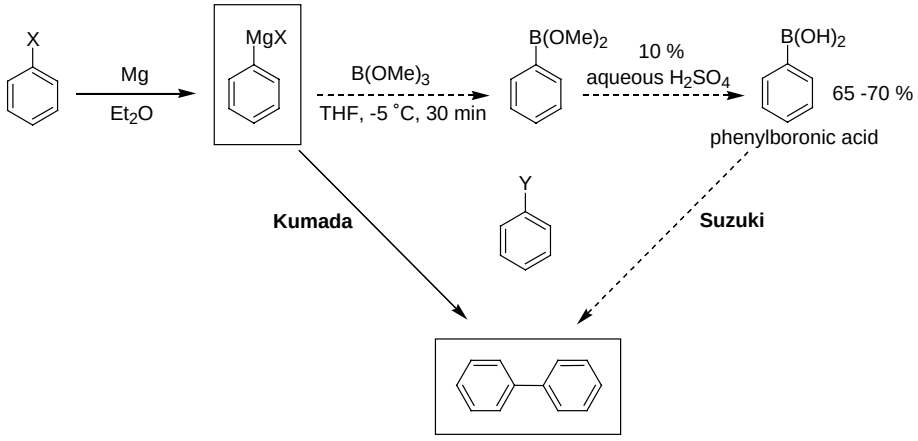
time. In addition, they tend to give side-reactions with a number of functional groups at room temperature or above.

Furthermore, only a limited number of Grignard reagents is commercially available. Nevertheless, the advantage of short-cutting the synthesis of biaryls surpasses these disadvantages in many cases. Although the Kumada reaction has been developed as one of the first cross-coupling reactions in 1972 [51,52], significant progress in the coupling of aryl chlorides in the presence of palladium catalysts has only been achieved very recently by Nolan [53]. Here, sterically demanding carbene ligands were crucial for good conversion of electron neutral and electron rich chloroarenes.

For comparison of different catalyst systems we tested four monocarbenepalladium(0) olefin complexes and three palladium(II) phosphine systems in the coupling of different aryl chlorides and 4-bromoanisole with phenylmagnesium bromide (Table 2).

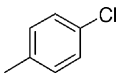
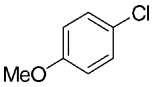
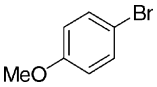
Among the carbene systems tested, highest yields were obtained with $[IPrPd(NQ)]_2$ (72–97% yield). IMes instead of IPr resulted in slightly to significantly lower yields.

Again, in most cases Pd(dvds) complexes showed low catalytic activity. Apparently the strong binding of the two vinyl groups to the Pd center blocks the catalyst and retards the oxidative addition reaction. Upon addition of NQ to IPrPd(dvds) the yield of coupling product is further decreased. Also in the inverse case of adding dvds to $[IPrPd(NQ)]_2$ only low product yields (<10%) are observed. To our surprise, only carbene complexes gave satisfactory



Scheme 3. Synthesis of biaryls via Kumada and Suzuki reactions.

Table 2
Testing of different catalysts in the phenylation of aryl chlorides.

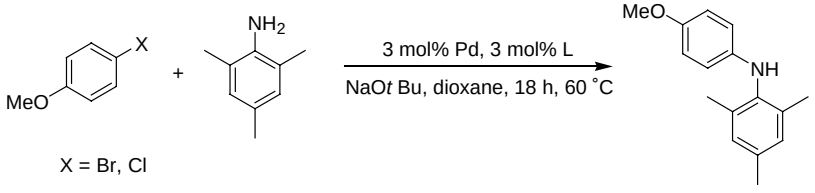
Entry	Substrate	Catalyst	Conversion (%)	Yield (%)
1		IprPd(dvds)	77	67
2		IprPd(dvds)/NQ	35	18
3		IMesPd(dvds)	8	2
4		**[IPrPd(NQ)]$_2$**	**96**	**90**
5		[IPrPd(NQ)]$_2$/dvds	24	4
6		**[IMesPd(NQ)]$_2$**	**94**	**85**
7		Pd(OAc)$_2$/BuPAd$_2$	12	5
8		Pd(OAc)$_2$/*o*-biph-PCy$_2$	78	15
9		Pd(OAc)$_2$/P*t*Bu$_3$	15	<1
10		IprPd(dvds)	21	6
11		IMesPd(dvds)	3	1
12		**[IPrPd(NQ)]$_2$**	**100**	**97**
13		[IMesPd(NQ)]$_2$	36	31
14		Pd(OAc)$_2$/BuPAd$_2$	3	3
15		**Pd(OAc)$_2$/*o*-biph-PCy$_2$**	**95**	**94**
16		Pd(OAc)$_2$/P*t*Bu$_3$	<1	0
17		IprPd(dvds)	29	16
18		IMesPd(dvds)	23	<1
19		**[IPrPd(NQ)]$_2$**	**80**	**72**
20		[IMesPd(NQ)]$_2$	22	9
21		Pd(OAc)$_2$/BuPAd$_2$	3	<1
22		**Pd(OAc)$_2$/*o*-biph-PCy$_2$**	**76**	**67**
23		Pd(OAc)$_2$/P*t*Bu$_3$	4	0
24		IprPd(dvds)	58	42
25		IMesPd(dvds)	26	5
26		**[IPrPd(NQ)]$_2$**	**99**	**97**
27		**[IMesPd(NQ)]$_2$**	**99**	**88**
28		Pd(OAc)$_2$	35	12
29		**Pd(OAc)$_2$/BuPAd$_2$**	**99**	**94**
30		**Pd(OAc)$_2$/*o*-biph-PCy$_2$**	**99**	**93**
31		Pd(OAc)$_2$/P*t*Bu$_3$	83	66

Reaction conditions: 2.0 mmol aryl halide, 2.4 mmol phenylmagnesium bromide, 2 mol% [Pd]; 4 mol% ligand, 10 ml dioxane, 80 °C, 3 h.

results in the coupling reaction of 1-chloro-2-fluorobenzene (Table 2, entries 1–9). Here, even the IPrPd(dvds) complex, which proved inactive in most of our studies, afforded the biaryl coupling product in good yields. Apart from the 2-(dicyclohexylphosphino)biphenyl/Pd(OAc)$_2$ system, which showed good performance in the coupling reactions of 4-chlorotoluene and 4-chloroanisole, phosphine-based in situ catalyst systems exhibited far inferior activity under these conditions. When changing from chloroarenes to 4-bromoanisole all catalysts tested, except for the dvds-derived complexes, gave moderate to good results in the Kumada coupling with PhMgBr.

2.3. Catalytic amination of aryl halides

Aromatic amines constitute important substructures in natural products as well as in industrially produced bulk and fine chemicals [54]. Interest in palladium-catalyzed C–N coupling reactions has grown constantly during the last years [8,33,55–69]. Important contributions to the development of the methodology came especially from the groups of Buchwald and Hartwig (Buchwald–Hartwig amination) [57–67]. Nowadays, a large variety of primary and secondary amines can be used as substrates for the palladium-catalyzed coupling of different aryl halides in the presence of



Scheme 4. Coupling of 4-chloro- and 4-bromoanisole with mesitylamine.

Table 3
Coupling of 4-chloro- and 4-bromoanisole with mesitylamine

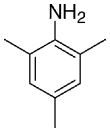
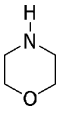
Entry	X	[Pd]	Ligand	Solvent	Conversion (%)	Yield (%)
1	Br	$Pd(dba)_2$	P*t*Bu_3	Toluene	100	94
2	Br	$Pd(dba)_2$	P*t*Bu_3	Dioxane	100	91
3	Br	$Pd_2(dba)_3$	*o*-biph-PCy_2	Dioxane	100	82
4	Br	$Pd(dba)_2$	IMesHCl	Dioxane	11	2
5	Br	IMesPd(dvds)	–	Dioxane	4	1
6	Br	$[IMesPd(BQ)]_2$	–	Dioxane	7	2
7	Br	$Pd(dba)_2$	IPrHCl	Dioxane	100	89
8	Br	IPrPd(dvds)	–	Dioxane	53	41
9	Cl	$Pd(dba)_2$	P*t*Bu_3	Toluene	65	64
10	Cl	$Pd(dba)_2$	P*t*Bu_3	Dioxane	100	93
11	Cl	$Pd_2(dba)_3$	*o*-biph-PCy_2	Dioxane	97	80
12	Cl	$Pd_2(dba)_3$	IMesHCl	Dioxane	4	0
13	Cl	IMesPd(dvds)	–	Dioxane	6	0
14	Cl	$[IMesPd(BQ)]_2$	–	Dioxane	10	5
15	Cl	$Pd_2(dba)_3$	IPrHCl	Dioxane	35	33
16	Cl	IPrPd(dvds)	–	Dioxane	7	6

Reaction conditions: 1.0 mmol aryl halide, 1.2 mmol amine, 3 mol% [Pd]; 3 mol% ligand, 1.5 Eq. NaO*t*Bu, 60 °C, 18 h.

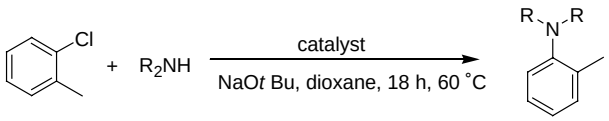
stoichiometric amounts of a strong base. As amination reactions are sensitive to electronic and steric changes in the substrates, we have chosen five different test reactions for the comparison of our catalyst systems. First, the coupling of 4-chloro- and 4-bromoanisole with mesitylamine was investigated in more detail (Scheme 4; Table 3).

In case of 4-bromoanisole good yields (82–94%) of the corresponding aniline were obtained in toluene or dioxane in the presence of in situ catalysts consisting of $Pd(dba)_2$ and carbene or phosphine ligands (Table 3, entries 1–3, 7). 1,3-Bis(2,6-diisopropylphenyl)imidazol-2-ylidene (IPr) gave much higher product yields compared to 1,3-dimesitylimidazol-2-ylidene (IMes) as carbene ligand (89% versus 2%). The isolated carbene Pd(dvds) complexes are much less active. Again the presence of dvds or BQ significantly retards the catalytic reaction. Even more pronounced are the effects for the coupling of 4-chloroanisole. For this reaction the best results (93%) are obtained in dioxane using $Pd(dba)_2$ and tri-*t*-butylphosphine as catalyst system. At 60 °C, which is a comparatively low reaction temperature for this transformation, the used carbene palladium complexes appear not reactive enough to allow efficient amination of deactivated aryl chlorides.

Table 4
Coupling of 2-chlorotoluene with different amines

Entry	Amine	Pd	Ligand	Solvent	Conversion (%)	Yield (%)
1		$Pd(dba)_2$	P*t*Bu_3	Dioxane	100	94
2		$Pd_2(dba)_3$	*o*-biph-PCy_2	Dioxane	69	65
3		IMesPd(dvds)	–	Dioxane	7	1
4		$[IMesPd(BQ)]_2$	–	Dioxane	76	71
5		$Pd_2(dba)_3$	IPrHCl	Dioxane	100	96
6		IPrPd(dvds)	–	Dioxane	6	2
7		$Pd(dba)_2$	P*t*Bu_3	Toluene	85	83
8		$Pd(dba)_2$	P*t*Bu_3	Dioxane	95	92
9		$Pd_2(dba)_3$	*o*-biph-PCy_2	Dioxane	100	71
10		IMesPd(dvds)	–	Dioxane	3	0
11		$[IMesPd(BQ)]_2$	–	Dioxane	86	28
12		$Pd_2(dba)_3$	IPrHCl	Dioxane	56	46
13		IPrPd(dvds)	–	Dioxane	30	23
14	$CH_3(CH_2)_3NH_2$	$Pd(dba)_2$	P*t*Bu_3	Dioxane	100	94
15		$Pd_2(dba)_3$	*o*-biph-PCy_2	Dioxane	93	86
16		IMesPd(dvds)	–	Dioxane	3	0
17		$[IMesPd(BQ)]_2$	–	Dioxane	7	5
18		$Pd_2(dba)_3$	IPrHCl	Dioxane	10	6
19		IPrPd(dvds)	–	Dioxane	7	2

Reaction conditions: 1.0 mmol aryl halide, 1.2 mmol amine, 3 mol% [Pd]; 3 mol% ligand, 1.5 Eq. NaO*t*Bu, 60 °C, 18 h.



Scheme 5. Coupling of 2-chlorotoluene with amines.

Next, the amination of 2-chlorotoluene with mesitylamine, morpholine, and *n*-butylamine, respectively, was investigated (Scheme 5; Table 4).

In general, palladium phosphine catalysts seem to be superior compared to the applied palladium carbene systems. Good to excellent product yields (65–94%) were obtained in the presence of P*t*Bu$_3$ or *o*-biph-PCy$_2$ and Pd$_2$(dba)$_3$ or Pd(dba)$_2$. Surprisingly, the catalyst performance of the Pd$_2$(dba)$_3$/IPrHCl system in the reaction of 2-chlorotoluene with the sterically more demanding mesitylamine turned out to be significantly different from that in the coupling with morpholine or *n*-butylamine. For the coupling of mesitylamine again IPr gave higher yields compared to IMes. Nevertheless, for this reaction IMes is a suitable ligand, too, if it is applied in form of the benzoquinonepalladium complex. If the analogous Pd(dvds) complex is used, almost no catalytic activity is observed. This shows once more the detrimental effect of dvds as co-ligand.

For the coupling of 2-chlorotoluene with morpholine IMes- and IPr-based catalysts gave only moderate yields (23–46%). In the case of [IMesPd(BQ)]$_2$ severe problems with reproducibility arised with exceedingly low selectivity for the amination product. Here, reductive dehalogenation leading to toluene becomes the major reaction pathway. In case of the coupling reaction of the primary amine *n*-butylamine the four tested carbenepalladium catalysts are not useful at all under our reaction conditions. However, in agreement with previous literature data palladium phosphine catalysts worked well.

3. Conclusions

Palladium-catalyzed C–C and C–N bond forming reactions of aryl chlorides and bromides have been studied in the presence of different palladium complexes. Depending on the type of coupling reaction good to excellent yields of the desired products are obtained in the presence of both carbene- and phosphine-based catalysts. For the first time a more detailed comparison of monocarbenepalladium(0) complexes with in situ generated palladium carbene and palladium phosphine complexes has been done. In general, the presence of dvds significantly retards catalysis in all reactions of aryl chlorides (Suzuki, Kumada, and Buchwald–Hartwig amination). However, some activity of Pd(0)(dvds) complexes is seen in coupling reactions of 4-bromoanisole. Clearly, monocarbenepalladium(0) quinone complexes are superior compared to the corresponding dvds complexes. These complexes are the most general and best catalytic systems in our hand for the Kumada reaction of aryl chlorides. To our surprise the in situ palladium phosphine and carbene catalysts, which consist of mixtures of palladium and ligands, often gave better yields in Suzuki and amination reactions compared to the isolated monocarbenepalladium(0) complexes. Nevertheless, these catalysts might be useful in special cases. It is important to note that the above drawn conclusions are based on the here applied reaction conditions. Although we are convinced that they are generally true, there might be special reaction conditions in which a different order of reactivity will be observed.

4. Experimental

Pd(dvds), carbene-Pd(dvds), and carbene-Pd(quinone) complexes are available at Umicore. They can be prepared according to published procedures. All coupling products have been identified by comparison of their GC/MS and NMR data with those of authentic samples.

4.1. Suzuki reaction of aryl halides and phenylboronic acid

A 25 ml Schlenk tube was charged under an argon atmosphere with the palladium catalyst (3 mol%, 0.06 mmol), Cs_2CO_3 (1.30 g, 4 mmol), and phenylboronic acid (0.37 g, 3 mmol). Then, dioxane (6 ml) and aryl halide (2 mmol) were added. The Schlenk tube was placed in a preheated oil bath (80 °C). After 2 h, the mixture was allowed to cool to r.t. and diluted with aqueous NaOH solution/diethylether (5/10 ml). Diethyleneglycol di-*n*-butylether (0.22 g) was added as internal standard for determining the product yields and conversions by GC. For reactions involving in situ systems a preformation of the active catalyst was necessary.

4.1.1. Pd(II) source

Sequential addition of imidazolium salt, palladium source, base, and solvent; stir at 80 °C for 1 h, then add phenylboronic acid and aryl halide.

4.1.2. Pd(0)(dvds)

Sequential addition of imidazolium salt, base, and solvent; stir at 80 °C for 1 h, then add Pd(0)(dvds), phenylboronic acid, and aryl halide.

4.2. Kumada reaction of aryl halides and arylmagnesium bromides

A 25 ml Schlenk tube was charged under an argon atmosphere with the palladium catalyst (2 mol%, 0.04 mmol), dioxane (10 ml), and aryl halide (2 mmol). It was placed in a preheated oil bath (80 °C) and the reaction was started by dropwise addition (1 min) of arylmagnesium bromide (2.4 ml, 2.4 mmol, 1.0 M in THF) via syringe. After 3 h, the mixture was allowed to cool to r.t. and hydrolyzed with

diluted aqueous HCl (10 ml, 1 M). The internal standard diethyleneglycol di-*n*-butylether (0.22 g) and diethylether (10 ml) were added and the product yields and conversions were determined by quantitative GC analysis.

4.3. Buchwald–Hartwig amination of aryl halides

A Schlenk flask was charged with the catalysts (0.03 mmol, 3 mol% Pd) and NaO*t*Bu (1.5 mmol) under an atmosphere of argon. Then, dioxane (2 ml), aryl halide (1.0 mmol), and amine (1.2 mmol) were added. The reaction mixture was stirred at 60 °C for 18 h. It was cooled to r.t. and quenched with water (1 ml). Diethyleneglycol di-*n*-butylether (100 μl) was added as internal standard followed by diethylether (8 ml). The organic layer was analyzed by GC.

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