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Efficient Palladium(II) Catalysis under Air. Base-Free Oxidative Heck Reactions at Room Temperature or with Microwave Heating

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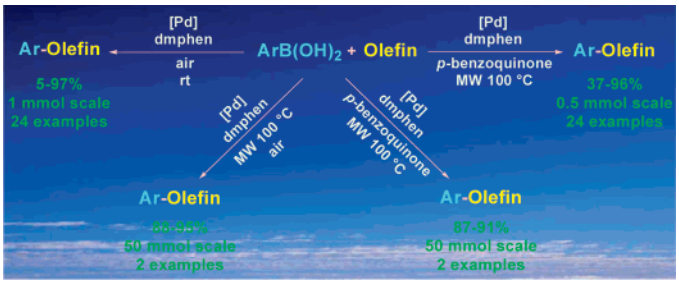

Scope and limitations of the base-free oxidative Heck reaction with arylboronic acids have been explored. Under our conditions, the dmphen−palladium(II)-catalyzed arylation proceeded with air or *p*-benzoquinone as reoxidants of palladium(0). We found that ambient temperature and mild aerobic conditions allow for the use of substrates sensitive to palladium(II)-catalyzed oxidation. Oxidative Heck couplings, employing different arylboronic acids, were smoothly and regioselectively conducted with both electron-rich and electron-poor olefins, providing high yields even with disubstituted butyl methacrylate, sensitive acrolein, and a vinylboronate ester. Controlled microwave processing was used to reduce reaction times from hours to minutes both in small scale and in 50 mmol scale batch processes.

Introduction

Independent research by Heck[1,2] and Mizoroki[3] in the early 1970s led to the discovery of a palladium(0)-catalyzed vinylic substitution reaction, now commonly referred to as the Heck reaction. This highly versatile and useful carbon−carbon bond forming methodology using aryl halides (or halide surrogates) as substrates has gained much interest over the years and is today a cornerstone in synthetic organic chemistry.[4−7] The palladium(II)-mediated version using organoboronic acids as arylmetal precursors was first described by Heck in 1975, using a full equivalent of palladium acetate.[8] This stoichiometric coupling did not cause much attention until almost two decades later when Uemura and co-workers reported the first catalytic protocol, allowing multiple turnovers of the catalytic cycle.[9] The first method using arylboronic acids and a dedicated reoxidant, $Cu(OAc)_2$, to regenerate Pd(II) from Pd(0), was introduced by Du et al. in 2001.[10] In 2003, Jung discovered that molecular oxygen could act as an efficient reoxidant of palladium.[11] Further, in 2004, we introduced the first ligand-modulated oxidative Heck reaction employing 2,9-dimethyl-1,10-phenanthroline (dmphen)[12] to facilitate the palladium reoxidation, to

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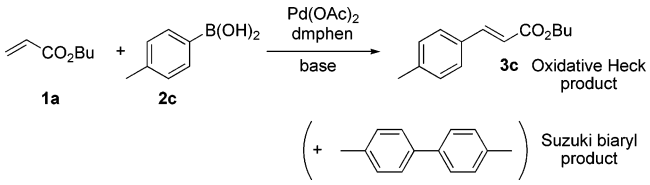
increase catalytic stability and to control the regioselectivity with electron-rich olefins.[13,14] In addition, with dmphen, palladium loadings could be reduced and atmospheric air could be used as the sole reoxidant. Very recently, Jung's research group published the first base-free oxidative Heck reaction,[15] including a plausible catalytic mechanism for the transformation.[15−17] This method employed oxygen gas for the essential Pd(II) recycling. The use of pure oxygen gas is, however, inconvenient, expensive, and associated with dangerous handling, reducing the utility of the procedure, especially for large-scale applications.

Arylboronic acids or esters are commonly employed substrates in the oxidative Heck reaction,[11,13−15,18,19] but other arylating agents have also been reported, e.g., arylstannanes,[20] arylsilanes,[21] arylmercury,[22] arylphosphonic acids,[23] arylbismuth,[24] and arylantimony[25] compounds. Many of these alternative organometallic or organometalloid reagents are unstable and produce byproducts that are often highly toxic and difficult to remove.[26] In contrast, arylboronic acids are comparatively air and moisture stable, relatively nontoxic, and easily accessible.[11,13,14,18,19,27,28] Another reason for the rising interest in the oxidative Heck transformation stems from the advancements made in environmentally benign reoxidation systems, mainly driven by the development of novel Pd(II)-catalyzed oxidation protocols.[17,29,30]

In modern synthetic organic chemistry laboratories, protocols for convenient and rapid transformations are highly desired. To meet these demands, dedicated microwave reactors have been developed for fast processing of sealed small-scale reaction mixtures.[31,32] However, among the large number of published microwave-assisted transformations only a limited number of pressurized medium- and large-scale reactions are available.[14,33,34]

SCHEME 1



This report addresses the base-free Pd(II)−dmphen-catalyzed oxidative Heck reaction and the impact of microwave-acceleration on it. We report herein (1) a new room-temperature method for chemo- and regioselective vinylation of arylboronic acids under air, (2) a small-scale microwave-accelerated oxidative Heck protocol using *p*-benzoquinone as reoxidant and dmphen as the regiocontrolling ligand, and (3) an oxidative Heck arylation performed on a 50 mmol scale using air and microwave energy to drive the reaction.

Results and Discussion

Reactions under Air. In previous work by our group in the field of the oxidative Heck chemistry there were indications that the choice of base had a distinct impact both on the product yield and the amount of detected homocoupled byproduct (Suzuki biaryl product).[35] To further investigate these observations, a model reaction was chosen and a series of different bases were screened at room temperature in open vessels using atmospheric air as the reoxidant (Scheme 1). The reaction system contained the olefin *n*-butyl acrylate (**1a**, 1 mmol), *p*-tolylboronic acid (**2c**, 2 equiv) as arylating agent, $Pd(OAc)_2$ (2 mol %) as Pd(II) source, dmphen (2.4 mol %) as the ligand, and a base (2 equiv) in acetonitrile (3 mL). The selected bases were all previously known to promote either Suzuki or oxidative Heck reactions, providing a wide span in base strength and structure.[36] Sodium hydroxide and cesium carbonate gave very little vinylic substitution product **3c** but predominantly homocoupled bitolyl, which under oxidative Heck reaction conditions is the expected product from a competing Suzuki-type pathway.[37−39] In accordance with literature data,[13] previously used oxidative Heck bases such as tertiary amines gave predominantly arylated olefin **3c**. Interestingly, a weak base such as sodium acetate worked almost as well as the commonly employed *N*-methylmorpholine (NMM), furnishing a slightly slower but higher yielding reaction without any concomitant biaryl formation.[40] This observation prompted us to run an experiment under air without addition of a base, and the result exceeded our expectations. The base-free process was even faster (18 h) than the corresponding

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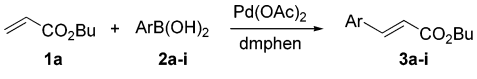
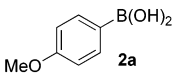
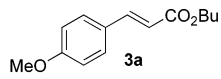
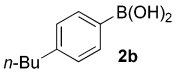
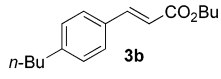
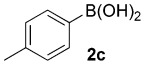
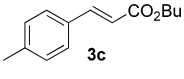
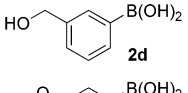
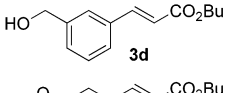
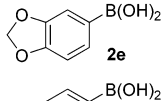
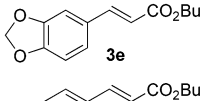
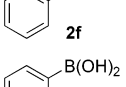
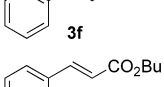
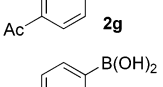
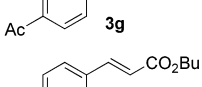
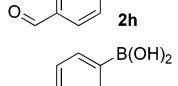
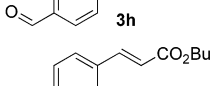
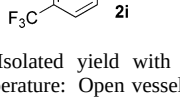
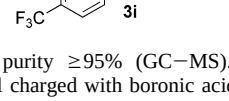
TABLE 1. Base-Free Oxidative Heck Arylations of *n*-Butyl Acrylate (1a) at Room Temperature under Air or with Microwave Heating and *p*-Benzoquinone



1a 2a-i 3a-i

entry	boronic acid	product	T (°C)	t	yield (%)[a]
1	 2a	 3a	rt 100	24 h 10 min	84 86
2	 2b	 3b	rt 100	18 h 10 min	49 68
3	 2c	 3c	rt 100 rt	18 h 10 min 18 h	97 94 97[b]
4	 2d	 3d	rt 100	24 h 10 min	83 85
5	 2e	 3e	rt 100	48 h 10 min	90 50
6	 2f	 3f	rt 100	24 h 10 min	93 89
7	 2g	 3g	rt 100	72 h 10 min	92 90
8	 2h	 3h	rt 100	48 h 10 min	95 77
9	 2i	 3i	rt 100	48 h 10 min	70 95

[a] Isolated yield with purity ≥95% (GC−MS). Reactions at room temperature: Open vessel charged with boronic acid (2.0 mmol), *n*-butyl acrylate (1.0 mmol), $Pd(OAc)_2$ (0.02 mmol), dmphen (0.024 mmol), and acetonitrile (3 mL) under vigorous stirring. Reactions at elevated temperatures: Microwave-transparent vessel charged with boronic acid (1.0 mmol), *n*-butyl acrylate (0.5 mmol), *p*-benzoquinone (0.5 mmol), $Pd(OAc)_2$ (0.01 mmol), dmphen (0.012 mmol), and acetonitrile (2 mL), sealed under air, and exposed to microwave irradiation. [b] Open vessel charged with boronic acid (100 mmol), *n*-butyl acrylate (50 mmol), $Pd(OAc)_2$ (1 mmol), dmphen (1.2 mmol), and acetonitrile (100 mL) under vigorous stirring.

NMM-promoted reaction (24 h) and furnished no detected byproducts. Thus, we decided to explore the synthetic scope of this air-promoted and base-free Heck protocol for arylation ofa wide variety of terminal olefins with different aryl boronic acids.

The preparative results of the arylation of **1a** (1 mmol) with nine different arylboronic acids (**2a**−**i**, 2 equiv) at room temperature are presented in Table 1. Remarkably, all entries show an improvement compared to previously reported reactions at 80 °C with the NMM base,[19] both in the form of faster reactions and in higher yields of cinnamic ester products. The only exception to this finding concerns *n*-butyl-functionalized **2b** (Table 1, entry 2), which afforded a disappointingly low yield of 49% at rt while a 96% yield was previously reported with NMM at 80 °C.[19] This result might partly be a consequence of the low solubility of **2b** at ambient temperature. Furthermore, the high yield of product **3g** was noteworthy because of the low reactivity of electron-deficient **2g** (Table 1, entry 7).[14] Since similar Pd(II) systems have also been used for oxidation of alcohols,[41] the chemoselectivity of the Pd(II)−dmphen−air catalytic combination was studied using a boronic acid equipped

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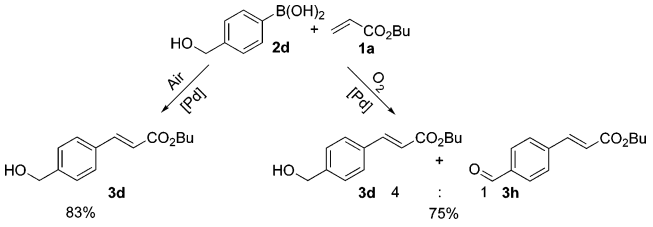
SCHEME 2



with a benzylic hydroxy group (Scheme 2). Product **3d** was isolated in 83% yield (Table 1, entry 4) without any traces of oxidized aldehydes **2h** and **3h** or the corresponding benzoic acid derivatives. This result implies that there is no need to protect a benzylic hydroxy group when employing this mild protocol. Interestingly, when the identical reaction was conducted under an atmosphere of oxygen gas as the reoxidant, a mixture of arylated alcohol **3d** and aldehyde **3h** (4:1) was produced in a total yield of 75%, demonstrating a reduced chemoselectivity utilizing oxygen gas as the Pd(0)-oxidant (Scheme 2). Likewise, substrate **2h**, carrying a sensitive aldehyde functionality, was selectively vinylated in high yield (95%) using our aerobic rt conditions (Table 1, entry 8). Finally, a large-scale experiment where 50 mmol of **1a** was arylated with **2c** (100 mmol) was performed to verify the scalability of the protocol, resulting in a 97% yield of isolated product **3c** (Table 1, entry 3).

Next, we selected arylboronic acids **2c** and **2g** to evaluate the air-promoted protocol with five additional mono- and disubstituted electron-deficient olefins (**1b**−**f**, Table 2) and three heteroatom-substituted alkenes (**1g**−**i**). Good yields were obtained for all reactions at ambient temperature using electron-poor olefins apart from the reaction between *N*,*N*-dimethylacrylamide **1c** and **2g** (Table 2, entry 5). The previously unreported Pd(II)-catalyzed arylation of phenyl vinyl sulfone **1e** required a 10 day reaction period with **2c** to obtain a satisfying yield (Table 2, entry 8).[42] As expected, it was further demonstrated that the regiodirecting scope of the dmphen ligand was broad, affording excellent regioselectivities with all olefins except **1f** (Table 2, entries 9, 10). In comparison to our standard base-containing air-promoted methodology,[19] all reactions were improved by omitting the base, with the exception of couplings with **1f**, which furnished slightly lower yields of **3s** and **3t** (entries 9 and 10). *n*-Butyl methacrylate (**1b**) provided a strong preference for styrene derivatives **3j** and **3l** (entries 2 and 3).[19] The sensitive acrolein **1d** was reacted with **2c** and **2g**, providing 82% of **3p** and 93% of **3q** (entries 6 and 7). Terminal arylation of the versatile vinylboronate ester[43] (**1g**) with **2c** furnished a yield of 67%, showing full selectivity for the Heck process (Table 2, entry 11). In contrast, when an identical reaction with the addition of 2 equiv of NMM as base was performed, extensive byproduct formation was obtained. A potential disadvantage of the base-free reaction system was realized employing electron-rich olefins **1h** and **1i** (Table 2, entries 12−15). In these cases, the acid-sensitive internally arylated Heck products underwent direct and extensive in situ hydrolysis, yielding the fully hydrolyzed methyl ketones **3v** and **3w** after addition of 1 M HCl (aq).

Small-Scale Microwave Reactions. Controlled microwave heating of small-scale reactions (0.2−20 mL volume) is

(42) Electron-poor **2g** produced only traces of product after 240 h.

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TABLE 2. Base-Free Oxidative Heck Reactions with Different Olefins and Arylboronic Acids 2c and 2g at Room Temperature under Air or with Microwave Heating

entry	olefin	product	T (°C)	t	yield (%)[a]
1	**1a**	**3c**	rt	24 h	98[b]
			120	1 h	74[c]
			120	10 min	40[c]
			100	20 min	95[d]
			100	10 min	91[e]
2	**1b**	**3j**	rt	24 h	85[f]
			100	10 min	77[g]
		3k	100	20 min	91[g,h]
3	**1b**	**3l**	rt	192 h	79[i]
			100	20 min	79[j]
		3m	100	20 min	88[d,j]
			100	20 min	87[h,j]
4	**1c**	**3n**	rt	24 h	71
			100	10 min	75
5	**1c**	**3o**	rt	120 h	22
			100	10 min	86
6	**1d**	**3p**	rt	24 h	82
			100	10 min	37
7	**1d**	**3q**	rt	48 h	93
			100	10 min	88
8	**1e**	**3r**	rt	240 h	87
			100	10 min	69
9	**1f**	**3s**	rt	48 h	75[k]
			100	10 min	95[k]
			120	1 h	60[c,l]
10	**1f**	**3t**	rt	72 h	70[m]
			100	10 min	94[m]
11	**1g**	**3u**	rt	24 h	67
			100	10 min	69
12	**1h**	**3v**	rt	72 h	70[n]
			100	10 min	94[o]
			120	1 h	10[c,o]
13	**1h**	**3w**	rt	240 h	5[n]
			100	10 min	96[o]
14	**1i**	**3v**	rt	24 h	91[n]
			100	10 min	78[o]
15	**1i**	**3w**	rt	120 h	15[n]
			100	10 min	38[o]

[a] Isolated yield with purity ≥95% (GC−MS). Reactions at room temperature: Open vessel charged with boronic acid (2.0 mmol), olefin (1.0 mmol), $Pd(OAc)_2$ (0.02 mmol), dmphen (0.024 mmol), and acetonitrile (3 mL) under vigorous stirring. Reactions at elevated temperatures: Microwave-transparent vessel charged with boronic acid (1.0 mmol), olefin (0.50 mmol), $Pd(OAc)_2$ (0.01 mmol), dmphen (0.012 mmol), *p*-benzoquinone (0.50 mmol), and acetonitrile (2 mL), sealed under air, and exposed to microwave irradiation. [b] 1 equiv of *p*-benzoquinone, under N_2. [c] Water as solvent, molecular oxygen as reoxidant. [d] 50 mmol scale, microwave irradiation, pressurized air (4 bar) as reoxidant. [e] 5 mmol scale, *p*-benzoquinone as reoxidant. [f] **3j**:**3k** (95:5) (GC−MS). Yield based on **3j**:**3k** mixture. [g] **3j**:**3k** (90:10) (GC−MS). Yield based on **3j**:**3k** mixture. [h] 50 mmol scale, microwave irradiation, 1 equiv of *p*-benzoquinone as reoxidant. [i] **3l**:**3m** (95:5) (GC−MS). Yield based on **3l**:**3m** mixture. [j] **3l**:**3m** (85:15) (GC−MS). Yield based on **3l**:**3m** mixture. [k] α/β (20:80) (GC−MS). Yield based on α/β mixture. [l] α/β (30:70) (GC−MS). Yield based on α/β mixture. [m] α/β (5:95) (GC−MS). Yield based on α/β mixture. [n] After hydrolysis with 1 M HCl (aq). [o] After in situ hydrolysis.

commonly performed with single-mode synthesizers using septa-sealed reaction vessels with restricted head space volume,[32,44] strongly limiting the utility of air as the Pd(0) reoxidant. Thus, the difficulties encountered in performing air-promoted chemistry with standard microwave equipment spurred our search for an alternative nongaseous oxidating agent. $Cu(OAc)_2$ was previously used in a ligand-free microwave method for oxidative Heck arylation of electron-poor alkenes.[18] This metal salt is, however, not compatible with the use of a dmphen-modulated Pd(II) catalyst due to competing ligand-copper coordination,[45,46] affording poor reoxidation of palladium, low catalytic activity, and deprived regioselectivity with electron-rich olefins. Hydrogen peroxide is known to oxidize arylboronic acids to their corresponding phenols and is therefore not suitable as reoxidant for these reactions.[47] Hence, we turned our attention toward the use of pure oxygen as the catalyst reoxidant. Since the use of a flammable solvent such as acetonitrile, sealed vessels, microwave heating, and oxygen gas is a hazardous combination, we attempted to utilize neat water as solvent using a 5 mL septum-sealed reaction vessel purged with oxygen gas. The methodology initially showed promising results for the reaction between **1a** and **2c**, providing a 74% yield of arylated acrylate **3c** (Table 2, entry 1). Unfortunately, lower yields were experienced for **3s** (60%) and especially for **3v** (10%) using pure water (Table 2, entries 9 and 12). Since the discussed reoxidants did not meet the expectations, we decided to investigate *p*-benzoquinone as a solid organic alternative.[48−50] To evaluate the efficiency of this reoxidant, air was substituted

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for *p*-benzoquinone (1 equiv) under an atmosphere of N_2 in the rt reaction between **1a** and **2c**, which furnished the product in an excellent yield of 98% (Table 2, entry 1). Rewardingly, the addition of 1 equiv of *p*-benzoquinone directly enabled us to transform the open air-promoted reaction methodology into a pressurized 0.5 mmol high-speed microwave protocol (Table 1 and 2). At a preset reaction temperature of 100 °C, reaction times were cut down from 18−240 h to only 10−20 min. The isolated yields were improved or remained essentially identical, apart from the cases of the acetal boronic acid **2e** (Table 1, entry 5), which was partially hydrolyzed under the harsher conditions, and the phenyl vinyl sulfone **1e** (Table 2, entry 8), which probably would have benefited from a longer reaction time. With the most unreactive reaction substrate combinations (Table 2, entries 3, 5, 8, 13, and 15), the elevated temperature conditions were crucial for efficient product formation. The identified protocol was suitable to a wide range of substrates, including the high dmphen-mediated selective internal arylation of **1h** and **1i**, although complete hydrolysis of branched Heck products **3v** and **3w** was unavoidable, and they were thus directly isolated as the analogous acetophenones (Table 2, entries 12−15). To establish if the microwave method could improve the reactivity while maintaining the regioselectivity in the β-elimination step, reactions of disubstituted **1b** with **2c** and **2g** were carried out. As shown in Table 2, entries 2 and 3, both reactions proceeded successfully, although the selectivity for internal olefins **3j** and **3l** was reduced slightly upon heating. A few sluggish olefins furnished depressing results also with microwave heating.[51]

Microwave Reactions on 50 mmol Scale. In order for microwave chemistry to evolve into a fully accepted and industrially relevant synthetic technology, there is a need to further improve available scale-up possibilities. Stoichiometric use of $Cu(OAc)_2$ or *p*-benzoquinone is generally not viable for large-scale synthesis, even though an electrochemical method for recycling of *p*-benzoquinone was recently published.[49,52] Neither is pure oxygen an appropriate alternative because of the cumbersome and hazardous handling, leaving air as the cheapest and best alternative. Due to the limited vessel size of single-mode microwave reactors, we turned our attention toward a one-vessel batch-type multimode reactor for scale-up attempts. This equipment featured a maximum output power of 1200 W for rapid temperature ramp-up, a precise field-tuning mechanism, efficient overhead paddle stirring (700 rpm) and a 350 mL sealable Teflon reaction vessel with the possibility to introduce pressurized air during irradiation.[53]

A medium-scale experiment was first performed with a single mode reactor using *p*-benzoquinone in order to stepwise increase the reaction scale under microwave conditions. Olefin **1a** (5 mmol) was arylated with **2c** (10 mmol) in a 20 mL sealed reaction vessel following the small-scale microwave methodology at 100 °C. The product (**3c**) was successfully isolated in 91% yield (Table 2, entry 1), allowing us to proceed to the large-scale batch reactor. Before trying the desired air-mediated reaction, two 50 mmol experiments were performed to verify the scalability of the *p*-benzoquinone-promoted small- and medium-scale microwave protocols. Methacrylate **1b** (50 mmol) was arylated with **2c** (100 mmol), or less reactive **2g** (100 mmol), employing *p*-benzoquinone (50 mmol). The two 100 mL experiments furnished satisfying yields of 91% for **3j/3k** and 87% for **3l/3m** (Table 2, entries 2 and 3). These results urged us to try the safer and more benign conditions using air as the reoxidant. By employing pressurized air (4 bar) and a closed reaction chamber at a temperature of 100 °C, *n*-butyl acrylate (**1a**, 50 mmol) was arylated with **2c** (100 mmol) and **1b** (50 mmol) was arylated with **2g** (100 mmol). Rewardingly, full conversions were realized after only 20 min of irradiation to be compared to the long reaction times (24 and 192 h) observed for the corresponding open vessel reactions at ambient temperature (Table 2, entries 1 and 3). The yields were also excellent with *n*-butyl acrylate product **3c** isolated in 95% yield and the butyl methyl cinnamate products **3l/3m** isolated as a 85:15 mixture in 88% yield. The large-scale, environmentally benign, aerobic protocol furnished equally high yields as the *p*-benzoquinone procotol, demonstrating the versatility of this oxidative Heck method. The temperature and pressure profiles of the large-scale microwave reactions are included in the Supporting Information.

Conclusions

We have demonstrated that the base-free, room-temperature oxidative Heck reactions using arylboronic acids as arylpalladium precursors can be regioselectively performed under air with different olefins. The reactions proceeded using only 2 mol % of $Pd(OAc)_2$ and were stabilized by the inexpensive 2,9-dimethyl-1,10-phenanthroline (dmphen) bidentate ligand. The use of air, instead of oxygen, as the reoxidant enabled efficient vinylic substitution without concomitant oxidation of benzylic alcohol or benzaldehyde functionalities. Small-scale arylations were carried out in sealed vessels under 10−20 min of 100 °C microwave heating utilizing *p*-benzoquinone as the essential catalyst oxidant. To demonstrate the scalability, four 50 mmol reactions were conducted in a dedicated microwave batch reactor, two with *p*-benzoquinone as reoxidant and two with atmospheric air as the reoxidant. The developed Heck method merits attention due to the convenient, non-expensive, and environmentally friendly experimental procedure. Further systematic investigations will be necessary to take full advantage of this mild method for C−C bond formation.

Experimental Section

General Procedure for Oxidative Heck Reactions at Room Temperature. A 50 mL vial was charged with olefin (1.0 mmol), $ArB(OH)_2$ (2.0 mmol), $Pd(OAc)_2$ (4.5 mg, 0.02 mmol), 2,9-dimethyl-1,10-phenanthroline (dmphen) (5.0 mg, 0.024 mmol), and acetonitrile (3.0 mL). The open vessel was vigorously stirred for the time specified in Tables 1 and 2. The reaction mixture was thereafter concentrated and dissolved in a small amount of dichloromethane. The crude product was purified on silica gel (ioshexane/ethyl acetate) by column chromatography to give the isolated products in yields stated in Tables 1 and 2.

(*E*)-3-(3-Hydroxymethylphenyl)acrylic Acid Butyl Ester (3d). Following the general procedure allowed the product to be isolated as a colorless oil in the yield stated in Table 1. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.94 (t, J = 7.4 Hz, 3H), 1.36−1.46 (m, 2H), 1.61−1.69 (m, 2H), 3.01 (s, 1H), 4.20 (t, J = 6.7 Hz, 2H), 4.65 (d, J = 0.7 Hz, 2H), 6.39 (d, J = 16.0 Hz, 1H), 7.30−7.35 (m, 2H), 7.35−7.40 (m, 1H), 7.46−7.47 (m, 1H), 7.60 (d, J = 16.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.7, 19.2, 30.7, 64.5, 64.8, 118.5,

(51) Phenyl vinyl sulfide and phenyl vinyl sulfoxide showed only traces of product (GC−MS) after 1 h of microwave heating at 100 °C (possibly due to sulfur poisoning of the catalyst). Sterically hindered ethyl 2-cyanoacrylate, benzylideneacetone and ethyl crotonate reacted very sluggishly with **2c** (less than 5% yield after 1 h of microwave heating at 100 °C).

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126.3, 127.3, 128.7, 129.0, 134.7, 141.6, 144.3, 167.1. MS (*m/z*, relative intensity, 70 eV, EI) 235 ($M^+ + H$, 100), 234 (M^+, 5), 161 (9), 143 (15), 131 (16). Anal. Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found: C, 71.48; H, 7.69.

General Procedure for Oxidative Heck Reactions under Microwave Irradiation. A test tube was charged with $Pd(OAc)_2$ (2.25 mg, 0.01 mmol), dmphen (2.5 mg, 0.012 mmol), and acetonitrile (1.0 mL) and stirred for 30 min. A 5 mL microwave-transparent process vial was charged with olefin (0.5 mmol), $ArB(OH)_2$ (1.0 mmol), *p*-benzoquinone (54 mg, 0.5 mmol), and acetonitrile (1.0 mL). The content from the test tube was added to the process vial, which was thereafter capped and exposed to microwave heating for the time stated in Tables 1 and 2 at 100 °C (for temperature/pressure profiles see the Supporting Information). The reaction vessel was thereafter cooled to room temperature, and the mixture was concentrated and the residue dissolved in a small amount of dichloromethane. The crude product was finally purified by column chromatography (silica gel, isohexane/ethylacetate) to give the isolated products in yields stated in Tables 1 and 2.

General Procedure for Oxidative Heck Reactions in H_2O under Microwave Irradiation. A test tube was charged with $Pd(OAc)_2$ (2.25 mg, 0.01 mmol), dmphen (2.5 mg, 0.012 mmol), and deionized water (1.0 mL) and stirred for 30 min. A 5 mL microwave-transparent process vial was charged with olefin (0.5 mmol), $ArB(OH)_2$ (1.0 mmol), and deionized water (1.0 mL). The $Pd(OAc)_2$ and dmphen slurry from the test tube was added to the process vial which was sealed with a septum and pressurized with air through a syringe. The pressurized vial was exposed to microwave heating for the time stated in Table 2 at 120 °C. The reaction mixture was thereafter cooled to room temperature and extracted with dichloromethane. The organic layers were combined and concentrated. The crude residue was thereafter purified by column chromatography (silica gel, isohexane/ethylacetate) to give the isolated products in yields stated in Table 2.

General Procedure for 50 mmol Oxidative Heck Reactions with Microwave Heating Employing *p*-Benzoquinone as Reoxidant. A 50 mL vial was charged with $Pd(OAc)_2$ (224.9 mg, 1.0 mmol), dmphen (249.7 mg, 1.2 mmol), and acetonitrile (10 mL) and stirred for 30 min. A 350 mL microwave-dedicated Teflon process vessel was charged with olefin (50.0 mmol), $ArB(OH)_2$ (100.0 mmol), *p*-benzoquinone (540.5 g, 50.0 mmol), and acetonitrile (90 mL). The $Pd(OAc)_2$ and dmphen slurry from the 50 mL vial was added to the Teflon process vessel, which was exposed to microwave heating for 20 min at 100 °C. The reaction mixture was thereafter flash cooled to room temperature, and the mixture was concentrated followed by extractive workup (dichloromethane/0.1 M NaOH (aq)). The organic layers were combined and concentrated. The crude product was thereafter purified by column chromatography (silica gel, isohexane/ethyl acetate) to give the isolated products in yields stated in Table 2.

General Procedure for 50 mmol Oxidative Heck Reaction with Microwave Heating Employing Air as Reoxidant. A 50 mL vial was charged with $Pd(OAc)_2$ (224.9 mg, 1.0 mmol), dmphen (249.7 mg, 1.2 mmol), and acetonitrile (10 mL) and the mixture stirred for 30 min. A 350 mL microwave-dedicated Teflon process vial was charged with olefin (50.0 mmol), $ArB(OH)_2$ (100.0 mmol), and acetonitrile (90 mL). The $Pd(OAc)_2$ and dmphen slurry from the 50 mL vial was added to the Teflon process vial before exposure to microwave heating for 20 min at 100 °C under a pressure of air (4 bar). The reaction mixture was thereafter flash cooled to room temperature, and the mixture was concentrated followed by extractive workup (dichloromethane/0.1 M NaOH (aq)). The organic layers were combined and concentrated. The crude product was thereafter purified by column chromatography (silica gel, isohexane/ethyl acetate) to give the isolated product in yields stated in Table 2.

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Supporting Information Available: Experimental procedures, spectroscopic data and references for known compounds, and temperature and pressure profiles of small- and large-scale microwave reactions. This material is available free of charge via the Internet at http://pubs.acs.org.

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