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Rhodium(III)-Catalyzed Directed *peri*-C−H Alkenylation of Anthracene Derivatives

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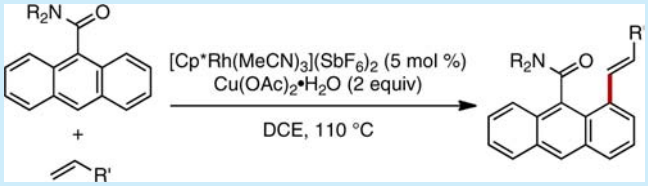
Supporting Information

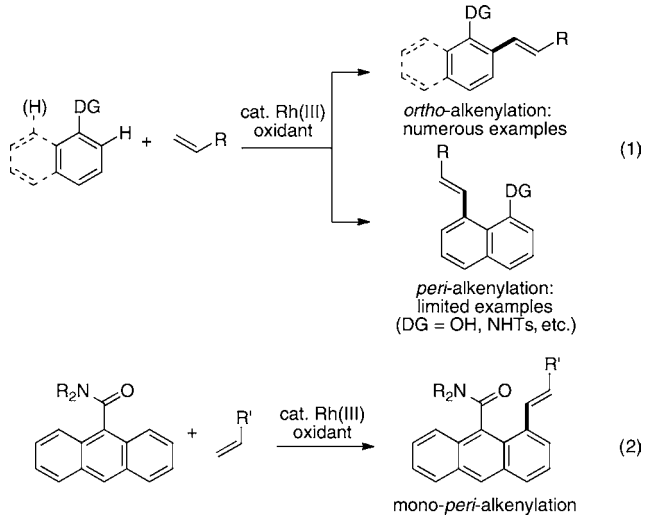
ABSTRACT: Rhodium(III)-catalyzed oxidative coupling reactions of anthracene-9-carboxylic acid derivatives with electron-deficient olefins are reported. A cationic rhodium(III) catalyst, in combination with a copper(II) oxidant, promotes selective monoalkenylation of anthracene-9-carboxamide, affording 1-alkenylanthracene-9-carboxamide in moderate to good yields. A similar catalytic system also promotes the reaction of anthracene-9-carboxylic acid and an electron-deficient olefin, which affords a lactone derivative through C−H alkenylation followed by intramolecular conjugate addition.



The past few decades have witnessed significant development in the transition-metal-catalyzed, directing-group-assisted functionalization of aromatic compounds.[1] With the extensive development of transition metal catalysts, heteroatom directing groups, and carbon- and heteroatom-based coupling partners, this strategy now offers a myriad of methods for the conversion of aromatic C−H bonds into C−C and C−heteroatom bonds, some of which have found applications in pharmaceuticals and other functional molecules.[2] Given this background as well as the importance of polycyclic aromatic hydrocarbons (PAHs) in organic functional materials,[3] it was thought somewhat strange that such polyaromatic compounds have not been frequently employed as platforms in directed C−H functionalization.[4]

In the past several years, there has been explosive development in rhodium(III)-catalyzed directed C−H functionalization reactions of aromatic compounds under oxidative and nonoxidative conditions.[5] With respect to oxidative *ortho*-alkenylation with olefins, rhodium(III) catalysis has allowed the use of benzoic acids,[6] acetanilides,[7] acetophenones,[8] benzamides,[8,9] benzoic esters,[10] aryl oxime ethers,[11] phenol carbamate,[12] and many others[13] as substrates, which form five- or six-membered rhodacycles as the key intermediates (Scheme 1, eq 1). On the other hand, polyaromatic substrates for directed *peri*-functionalization have been mostly limited to 1-naphthol and 1-aminonaphthalene derivatives that can form a five-membered rhodacycle upon *peri*-C−H activation,[14] and other 1-functionalized naphthalene derivatives typically undergo C−H activation at the *ortho*-position rather than the *peri*-position. To our knowledge, functionalized anthracenes and higher acenes, including readily available anthracene-9-carboxylic acid and its derivatives, have been rarely used as substrates for the rhodium(III) catalysis.[15] With our recent development of a synthetic route to anthracene derivatives that features cobalt-catalyzed branch-selective addition of aromatic imines to styrenes,[16,17] we became interested in the possibility of directed

Scheme 1. Rhodium(III)-Catalyzed Directed Oxidative C−H Alkenylation with Olefins



and nondirected C−H functionalization of such PAH derivatives. Here, we report on a rhodium(III)-catalyzed oxidative coupling reaction of an anthracene-9-carboxamide and an electron-deficient olefin, which results in selective monoalkenylation of the proximal *peri*-position of the anthracene core (Scheme 1, eq 2).

Our effort was initially focused on the alkenylation of anthracen-9-yl(pyrrolidin-1-yl)methanone **1a** with ethyl acrylate **2a** (Table 1). Upon screening various reaction conditions, we managed to promote the desired reaction using [Cp*Rh(MeCN)$_3$](SbF$_6$)$_2$ (5 mol %), Cu(OAc)$_2$·H$_2$O (2 equiv), and

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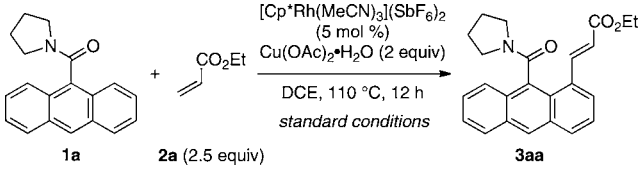
Table 1. Screening of Reaction Conditions[a]



1a 2a (2.5 equiv) 3aa

entry	deviation from standard conditions	yield (%)[b]
1	none	72[c]
2	$[Cp^*RhCl_2]_2/AgSbF_6$ as the catalyst[d]	49
3	PhCl instead of DCE	65
4	*t*-AmylOH instead of DCE	36
5	1,4-Dioxane instead of DCE	24
6	DMF instead of DCE	5
7	AgOAc instead of $Cu(OAc)_2·H_2O$	49
8	Ag_2CO_3 instead of $Cu(OAc)_2·H_2O$	35

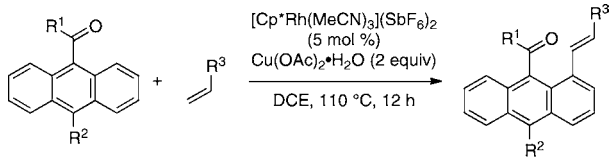
[a]The reaction was performed on a 0.2 mmol scale. [b]Determined by ^1H NMR using mesitylene as an internal standard. [c]Isolated yield. [d]$[Cp^*RhCl_2]_2$ (2.5 mol %) and $AgSbF_6$ (10 mol %) were used.

1,2-dichloroethane (DCE) as the catalyst, oxidant, and solvent, respectively, which afforded the *peri*-monoalkenylated product **3aa** in 72% yield (Table 1, entry 1). The use of a combination of Cp^*RhCl_2 dimer and $AgSbF_6$ instead of the cationic rhodium catalyst resulted in a lower yield (Table 1, entry 2). While a comparable result was obtained using PhCl instead of DCE (Table 1, entry 3), more polar and coordinating solvents such as *t*-AmylOH, 1,4-dioxane, and DMF were detrimental to the reaction (Table 1, entries 4–6). Replacement of the Cu(II) oxidant to a Ag(I) oxidant such as AgOAc and Ag_2CO_3 led to lower yields (Table 1, entries 7 and 8).

Under the conditions in entry 1, the unreacted starting material **1a** was mostly recovered and no identifiable byproduct was detected. Further modifications of the reaction parameters (e.g., catalyst loading, amount of **2a**, temperature) have not allowed us to achieve significant improvement of the conversion of **1a** and the yield of **3aa**. It should be noted that, when using 10 equiv of **2a**, we observed the formation of a small amount of a *peri*-dialkenylation product (<5% yield according to ^1H NMR analysis).

With the optimized reaction conditions in hand, we next explored the scope of anthracene amides and olefins for the present *peri*-alkenylation reaction (Table 2). The reactions of **1a** with acrylates proceeded smoothly regardless of the alkyl group, affording the corresponding alkenylation products **3aa**–**3ae** in yields of 61%–80% (Table 2, entries 1–5), while phenyl vinyl sulfone reacted more sluggishly (Table 2, entry 6). Acrylonitrile and styrene failed to participate in the reaction (Table 2, entries 7 and 8). In the coupling with methyl acrylate **2b**, pyrrolidine-derived **1a** afforded the highest yield among the tertiary amides examined (Table 2, entry 1), followed by those derived from other cyclic amines (Table 2, entries 9 and 10) and then by *N*,*N*-dimethyl- and *N*,*N*-diethylamides (Table 2, entries 11 and 12). *N*-Isopropylamide also underwent the *peri*-alkenylation reaction with **2b** to afford the desired product **3fb** in a moderate yield of 48% (Table 2, entry 13). Note that, in this case, intramolecular cyclization of the amide group and the acrylate moiety was not observed. Anthracene-9-carboxamides bearing extra substituents such as aryl, alkynyl, amino, and bromo groups on the 10-position all participated in the reaction with **2b**, affording the corresponding alkenylation products **3gb**–**3kb** in reasonable yields (Table 2, entries 14–18).

Table 2. Scope of *peri*-C–H Alkenylation[a]



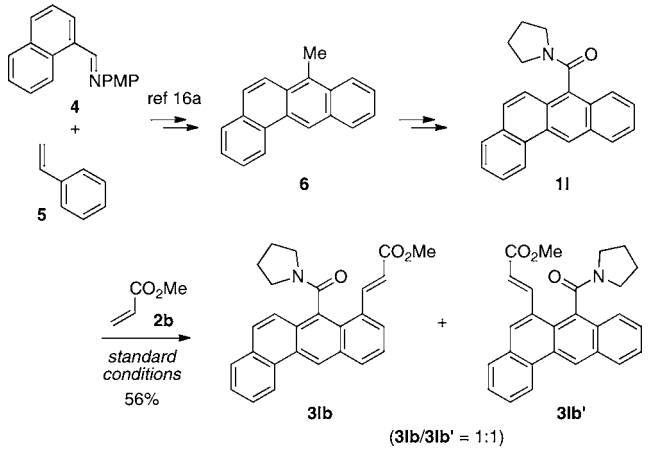
1 2 (3 equiv) 3

entry	R^1	R^2	R^3	3, yield (%)[b]
1[c]	pyrrolidinyl	H	CO_2Et	**3aa**, 72
2	pyrrolidinyl	H	CO_2Me	**3ab**, 80
3	pyrrolidinyl	H	CO_2Bu	**3ac**, 74
4	pyrrolidinyl	H	CO_2t-Bu	**3ad**, 64
5	pyrrolidinyl	H	CO_2Bn	**3ae**, 61
6	pyrrolidinyl	H	SO_2Ph	**3af**, 36
7	pyrrolidinyl	H	CN	0
8	pyrrolidinyl	H	Ph	0
9	piperidinyl	H	CO_2Me	**3bb**, 66
10	morpholinyl	H	CO_2Me	**3cb**, 61
11	NMe_2	H	CO_2Me	**3db**, 48
12	NEt_2	H	CO_2Me	**3eb**, 42
13	NH*i*Pr	H	CO_2Me	**3fb**, 48
14	pyrrolidinyl	Ph	CO_2Me	**3gb**, 70
15	pyrrolidinyl	*m*-Tol	CO_2Me	**3hb**, 71
16	pyrrolidinyl	PhC≡C	CO_2Me	**3ib**, 64
17	pyrrolidinyl	morpholinyl	CO_2Me	**3jb**, 64
18	pyrrolidinyl	Br	CO_2Me	**3kb**, 56

[a]The reaction was performed on a 0.2 mmol scale. [b]Isolated yield. [c]2.5 equiv of ethyl acrylate were used.

As briefly mentioned previously, the combination of cobalt-catalyzed branch-selective addition of aryl aldimine to styrene and subsequent indium-catalyzed dehydrative cyclization allows for the facile synthesis of methylated anthracene derivatives, such as 7-methyltetraphene **6** (Scheme 2).[16a] The methyl group

Scheme 2. Alkenylation of Tetraphene-7-carboxamide[a]



[a]See the Supporting Information for the conversion of **6** to **1l**.

of **6** was then converted to a tertiary amide group in a few steps, thus affording unsymmetrical tetraphene-7-carboxamide **1l**. Because both of the *peri*-positions of **1l** are sterically unhindered, not unexpectedly, the rhodium(III)-catalyzed reaction of **1l** and **2b** afforded a mixture of regioisomers **3lb** and **3lb′** in an approximate ratio of 1:1.

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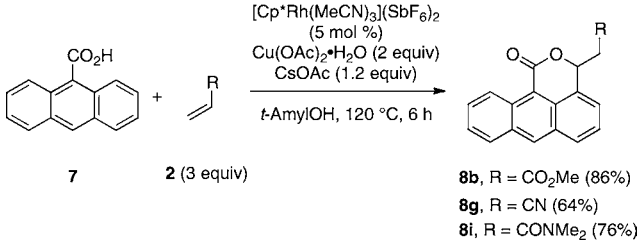
Oxidative *peri*-functionalization of parent anthracene-9-carboxylic acid **7** was also achieved (Scheme 3). Thus, the

Scheme 3. *peri*-C−H Alkenylation/Cyclization of Anthracene-9-carboxylic Acid[a]

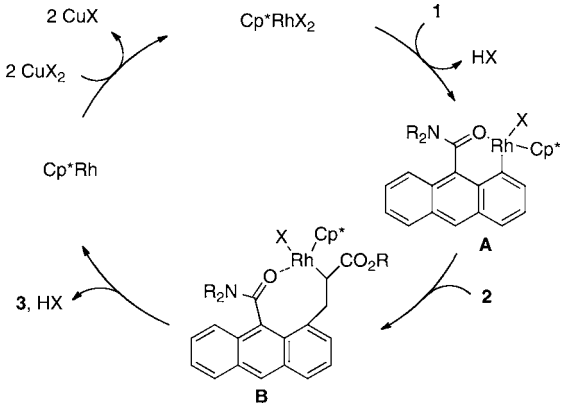


[a]The reaction was performed on a 0.2 mmol scale.

reactions of **7** and electron-deficient olefins proceeded under modified reaction conditions employing CsOAc as an additive and *tert*-amyl alcohol instead of DCE as a solvent, thus affording lactone derivatives **8b**, **8g**, and **8i** in good yields, presumably through C−H alkenylation followed by intramolecular conjugate addition.[6] Note that the reaction of **7** and **2b** in the absence of CsOAc afforded **8b** in a lower yield of 70%. We speculate that CsOAc acts as a base to facilitate the formation of rhodium(III) anthracene-9-carboxylate, which would be an intermediate prior to C−H activation.[18]

While our attempts to characterize a reaction intermediate have not been successful, we assume that the present *peri*-alkenylation reaction involves a catalytic cycle that is essentially the same as those proposed for related *ortho*-alkenylation reactions (Scheme 4).[5] Thus, the rhodium(III) catalyst

Scheme 4. Plausible Catalytic Cycle



undergoes *peri*-C−H activation of the anthracene substrate **1** to form a rhodacycle **A** with concomitant deprotonation. Insertion of olefin **2** into the C−Rh bond of **A** gives an alkylrhodium intermediate **B**, which may or may not retain the chelation of the amide oxygen atom. Subsequent *β*-hydride elimination results in the formation of the product **3** and reduction of rhodium(III) to rhodium(I). Reoxidation of the rhodium(I) species with the copper(II) oxidant regenerates the active rhodium(III) catalyst.

Table 3 summarizes the UV−visible absorption and fluorescence properties of **1a** and selected *peri*-alkenylated anthracene derivatives. The starting material **1a** showed multiple absorption and emission peaks reflecting the vibrational fine structure, which is characteristic to anthracene and

Table 3. Photophysical Properties of Selected Alkenylated Anthracenes[a]

entry	1 or 3	λ_{max}/nm	log ε	λ_{em}/nm[b]	Φ_F[c]
1	**1a**	347, 366, 385	4.18, 4.36, 4.33	389, 412, 436	0.18
2	**3ab**	391	4.24	473	0.42
3	**3af**	394	4.08	485	0.44
4	**3gb**	401	4.15	484	0.44
5	**3ib**	417, 438	4.52, 4.51	487	0.55
6	**3jb**	409	4.13	467	0.028

[a]In CH_2Cl_2. [b]Excited at the longest absorption maxima wavelength except for **1a** (366 nm) and **3ib** (417 nm). [c]Determined with anthracene as a standard.

its simple derivatives (Table 3, entry 1). Such fine structures disappeared in most of the *peri*-alkenylated derivatives (Table 3, entries 2−6), except for the 10-alkynyl derivative **3ib** which showed two absorption maxima (Table 3, entry 5). Expectedly, the *peri*-alkenyl group of **3ab** and **3af** caused a substantial red shift of λ_{max} and λ_{em} compared to **1a** (Table 3, entries 2 and 3), while further influence of the 10-substituent (**3gb**, **3ib**, **3jb**) was relatively small (Table 3, entries 4−6). The *peri*-alkenylated derivatives showed light blue-green fluorescence (Table 3, entries 2−5), with the exception of 10-morpholino derivative **3jb** which was almost nonfluorescent presumably due to excited state intramolecular electron transfer (Table 3, entry 6).

In summary, we have demonstrated that a rhodium(III) catalyst is capable of catalyzing *peri*-C−H alkenylation of anthracene-9-carboxamides and anthracene-9-carboxylic acid with electron-deficient alkenes under oxidative conditions. Further improvement of the catalytic activity and exploration of other carbon- and heteroatom-based coupling partners may lead to versatile methods for the functionalization of anthracene and higher acenes, producing functionalized polyaromatic compounds that are not readily accessible by conventional methods.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details and characterization of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(18) The addition of CsOAc to the reaction of **1a** and **2a** had a detrimental effect (52% yield). We consider that the amide oxygen serves as an effective directing group for C−H activation without deprotonation.