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J. Org. Chem., **Just Accepted Manuscript** • Publication Date (Web): 05 Sep 2013

Palladium-Catalyzed Direct *ortho* Alkoxylation of Aromatic Azo Compounds with Alcohols

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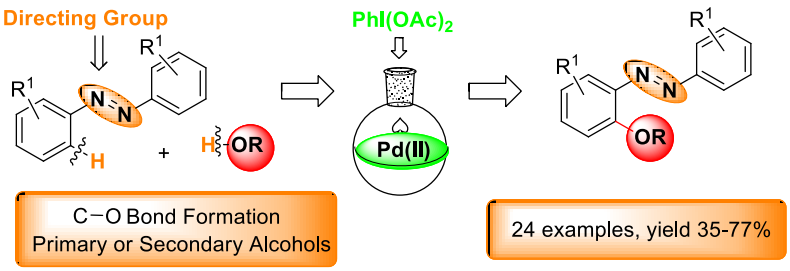


ABSTRACT: An efficient and highly regioselective synthesis of 2-alkoxyl aromatic azo compounds was developed via the palladium(II)-catalyzed alkoxylation of azobenzene derivatives directed by azo group using alcohols as the alkoxylation reagents and $PhI(OAc)_2$ as the oxidant. The method was applicable to both primary and secondary alcohols and the moderate to good yields were achieved.

In the past decade, transition-metal-catalyzed direct functionalization of unreactive C-H bonds have achieved great success and been applied in the syntheses of many useful polyfunctional compounds. A series of coordinating groups were employed as the directing groups in this strategy.[1] Compared to the formation of C–C bond, the reports of the formation of C–O bond are less well established, maybe because of the electronegativity of the elements as well as the metal–ligand bond strength.[2] Introducing alkoxy group on the aromatic ring has great value in organic synthesis because of the strong electron-donating conjugation effect of this group. And also, the aryl

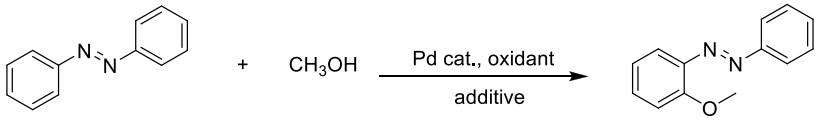
ether functionality is a common motif of pharmaceutical, functional materials and many other fine chemicals.[3] Therefore to develop new methodology of direct alkoxylation of C–H bond is becoming a valuable and atom-economical strategy to construct this structural block.[4] A few research groups, including our group reported the directed *ortho*-alkoxylation of the C(sp^2)−H bonds of arenes or C(sp^3)−H bonds catalyzed by palladium, in which oxime ether, *N*-methoxyamide, amide and cyano were respectively used as the directing goups.[5] These successful results push us to continue to carry out our research in this area.

Aromatic azo derivatives, a group of important conjugated compounds, are widely used not only in the traditional chemical industry, such as dyes and pigments,[6] but more noticeably, in many newly rising areas of science and technology, such as photochemical molecular switch, super-molecular chemistry of host-guest recognition, self-assembly liquid crystal material, analysis of biomedical imaging and chemical, light driven molecular motor, energy conversion and so on.[7] Therefore the synthesis of aromatic azo derivatives, as well as the modification and functionalization to these compounds in recent years have once again become the academic hot-spot. A few examples concerned with the palladium-catalyzed functionalization to aromatic azo compounds.[8] Very recently, palladium-catalyzed *ortho*-acylation and halogenation of aromatic azo compounds were reported respectively.[9] A rhodium(III)-catalyzed C−H bond addition of azobenzenes to aldehydes was also developed.[10] Herein we want to describe a Pd−catalyzed *ortho*-alkoxylation of the C(sp^2)−H bond at aromatic ring directed by azo group using alcohols as alkoxylation reagents to synthesize 2-alkoxyl aromatic azo compounds.

We started to optimize the reaction conditions by using azobenzene (**1a**) as the substrate and methanol (**1b**) as both the alkoxylation reagent and solvent. In the absence of $Pd(OAc)_2$, the reaction could not proceed at all. The presences of $Pd(OAc)_2$ (10 mol%) and an oxidant $PhI(OAc)_2$ led to a formation of the desired monomethoxylation product **3aa** with very high selectivity. In order to improve the yield, A series of oxidants were tested, in which no conversion was observed when $Cu(OAc)_2$, AgOAc, BQ or O_2 was used as the oxidant (entries 12~15), and a very low yield was obtained when $K_2S_2O_8$ or $(NH_4)_2S_2O_8$ was used (entries 10, 11). $PhI(OAc)_2$ was proved to be the best

oxidant, and the appropriate amount of it was 2 eq (entries 1, 9). Some additives such as AcOH, TFA, TsOH and CH_3SO_3H were also tested. In the presence of AcOH, the yield did not increase evidently (entries 2~4), but the presence of TFA, TsOH and CH_3SO_3H was obviously not favorable for this reaction (entries 5~7). So no additive was employed in our determined reaction conditions. Other palladium catalysts such as $PdCl_2$, $PdCl_2(CH_3CN)_2$ and $PdCl_2(PPh_3)_2$ showed low catalytic activity (entries 16~18), while Ru and Rh catalysts $[RuCl_2(p\text{-cymene})]_2$ and $[RhCp^*Cl_2]_2$ demonstrated entirely no efficiency to this reaction (entries 19, 20). Different reaction temperatures were also investigated. At 80 ^oC, the best result was obtained. Decreasing the temperature to 60 ^oC or room temperature brought the reduction of the yield. And also, there was no obvious promotion while increase the temperature to 100 ^oC (entry 1). Besides, the yield decreased sharply when 5 mol% $Pd(OAc)_2$ was used (entry 8).

Table 1. Optimization of the Reaction Conditions[a]



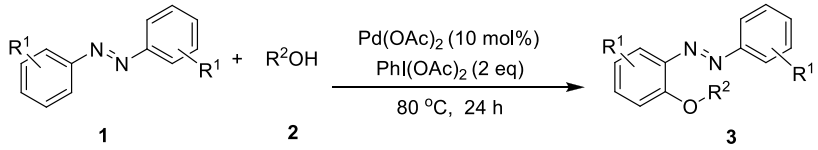
1a **2a** **3aa**

entry	catalyst	oxidant (eq)	additive (eq)	yield (%)[b]
1	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	none	75 (23, 62, 73)[c]
2	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	AcOH (1)	73
3	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	AcOH (5)	70
4	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	AcOH (10)	71
5	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	TFA (1)	<10
6	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	TsOH (1)	<10
7	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	CH_3SO_3H (1)	<10
8	$Pd(OAc)_2$	$PhI(OAc)_2$ (2)	none	47[d]

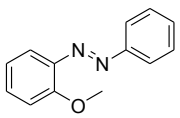
9	$Pd(OAc)_2$	$PhI(OAc)_2$ (1)	none	43
10	$Pd(OAc)_2$	$K_2S_2O_8$ (2)	none	13
11	$Pd(OAc)_2$	$(NH_4)_2S_2O_8$ (2)	none	23
12	$Pd(OAc)_2$	$Cu(OAc)_2$ (2)	none	0
13	$Pd(OAc)_2$	AgOAc (2)	none	0
14	$Pd(OAc)_2$	BQ (2)	none	0
15	$Pd(OAc)_2$	O_2 (1atm)	none	0
16	$PdCl_2$	$PhI(OAc)_2$ (2)	none	55
17	$PdCl_2(CH_3CN)_2$	$PhI(OAc)_2$ (2)	none	25
18	$PdCl_2(PPh_3)_2$	$PhI(OAc)_2$ (2)	none	59
19	$[RuCl_2(p\text{-cymene})]_2$	$PhI(OAc)_2$ (2)	none	0
20	$[RhCp^*Cl_2]_2$	$PhI(OAc)_2$ (2)	none	0

[a]Unless otherwise specified, all the reactions were carried out in a sealed tube in the presence of azobenzene (**1a**, 0.50 mmol), methanol (**2a**, 2mL), catalyst (10 mol%) and oxidant (1 mmol) under air atmosphere at 80 °C for 24 h. [b]Isolated yields. [c]At room temperature, 60 and 100 °C, respectively. [d]$Pd(OAc)_2$ (5 mol%) was used.

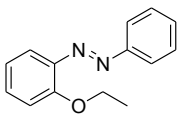
Table 2. **The *ortho*-Alkoxylation of Azobenzene Derivatives with Alcohols**[a]



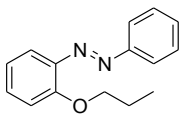
1 **2** **3**



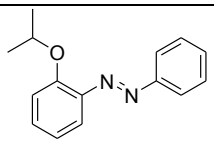
3aa 75%



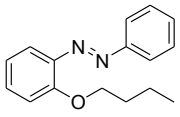
3ab 63%



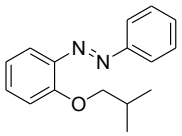
3ac 77%[b]



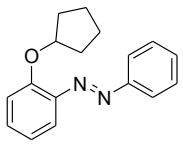
3ad 55%[b]



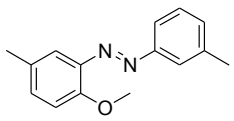
3ae 62% (36 h)[b]



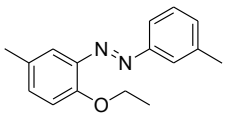
3af 65% (36 h)[b]



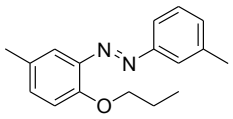
3ag 52% (72 h)[b]



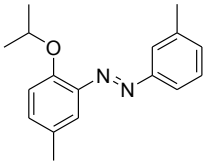
3ba 69%



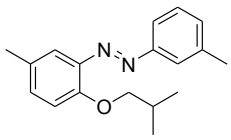
3bb 57%



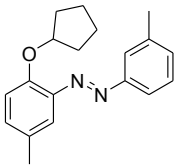
3bc 70%[b]



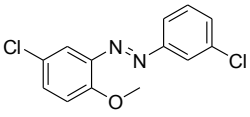
3bd 51%[b]



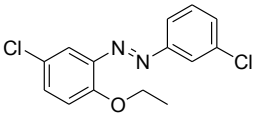
3bf 67%[b]



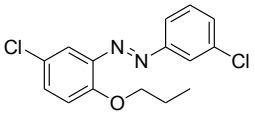
3bg 47%[b]



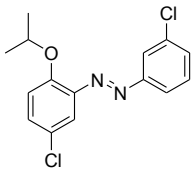
3ca 62%



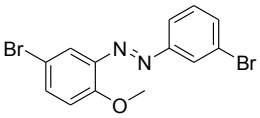
3cb 43%



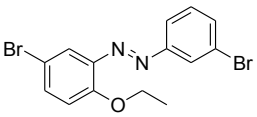
3cc 59% (100 °C, 48 h)[b]



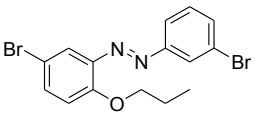
3cd 35% (100 °C, 72 h)[c]



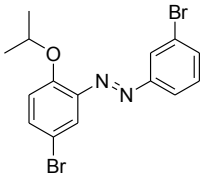
3da 66%



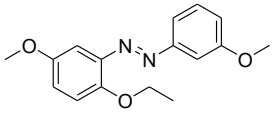
3db 47%



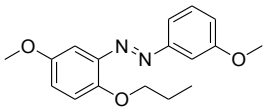
3dc 65% (100 °C, 36 h)[b]



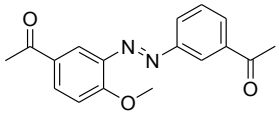
3dd 40% (100 °C, 72 h)[b]



3eb 55%



3ec 51%[b]



3fa 42%

[a]Unless otherwise specified, all reactions were carried out with aromatic azo compound (**1**, 0.5 mmol), alcohol (**2**, 2mL), $Pd(OAc)_2$ (10 mol %), $PhI(OAc)_2$ (1.0 mmol) under air atmosphere at 80 °C for 24 h. All listed yields are isolated one. [b]20 equiv AcOH was used as additive.

With suitable conditions for the methoxylation of azobenzene in hand, the reactivities of different alcohols as the alkoxylation reagents were investigated. The results were revealed in Table 2. To our delight, the alkoxylation with ethanol (**2b**) afforded product **3ab** in a yield of 63%. Unfortunately, propanol (**2c**) and isopropanol (**2d**) did not undergo the reaction smoothly to give corresponding alkoxylation products in the same condition. Then we attempted to employ some additive. To our surprise, the propoxylation and isopropoxylation products (**3ac**, **3ad**) were obtained with the yield of 77% and 55% respectively by adding 20 equiv AcOH. Under this reaction condition, the alkoxylation

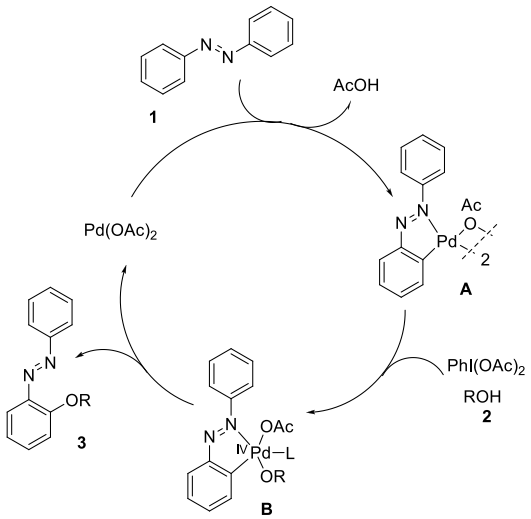
products with some other primary or secondary alcohols such as butanol (**2e**), isobutanol (**2f**) and cyclopentanol (**2g**) were achieved in moderate yield for the reaction time of 36-72 hours (**3ae**~**3ag**), while more sterically hindered *tert*-butyl alcohol failed to provide the desired product, which was similar to the previous reported alkoxylation reactions.[5] It was interesting that the reaction gave the monoalkoxylation products with very high selectivity for the alcohols we used.

After screening of different alcohols, we explored the scope of differently substituted azobenzenes. Substituents on the aromatic moiety of aromatic azo compounds influence the efficiency of this coupling reaction significantly. It was unfortunate that the method seems not very efficient to the *ortho*- or *para*-substituted azobenzene derivatives in the present reaction conditions. For example, for the methoxylation of 2,2'-dimethylazobenzene and 4,4'-dimethylazobenzene, only trace desired products generated. However, a range of *meta*-substituted azobenzenes could be adopted in our alkoxylation methodology. The reaction of azobenzene derivatives having an electron-donating group such as methyl or methoxy on the *meta* position of phenyl ring proceeded smoothly to give the corresponding products. By using primary alcohols (methanol, ethanol, propanol, isobutanol), the satisfactory yields could be obtained in 51%~70% (**3ba**~**3bc**, **3bf**, **3eb**~**3ec**) while the secondary alcohol (isopropanol, cyclopentanol) giving lower yield of 51% and 47% (**3bd**, **3bg**), respectively. Alkoxylation of aromatic azo compounds bearing a weak electron-withdrawing group (-Cl, -Br) group at the *meta* position of the phenyl ring was less efficient apart from methoxylation reaction (**3ca**, **3da**). For example, the propoxylation and isopropoxylation needed higher temperature (100 ^{o}C) and longer reaction time (36~72 h) to afford the products (**3cc**, **3cd**, **3dc**, **3dd**). Other electron-withdrawing group, such as acetyl, could also be functionalized to bring out the desired product, albeit with a relatively low yield (**3fa**).

On the basis of previous related studies[5,9] and our experiments, a possible mechanism of this palladium-catalyzed alkoxylation of aromatic azo compounds is proposed as shown in Scheme 1. First, the coordination of azobenzene (**1**) with Pd (II) catalyst and subsequent C-H activation to undergo cyclopalladation formed the palladacycle **A**. Then the aryl palladium intermediate **A** was oxidized to Pd (IV) species **B** by $PhI(OAc)_2$ in the presence of alcohol. Next, the final product **3** was obtained via

reductive elimination of **B**, followed by the regeneration of Pd (II) catalyst. In addition, Ritter[11] proposed a Pd(II)/Pd(III) catalytic cycle through a bimetallic Pd(III) complex for a similar directed C−O bond formation reactions. Recently, Sunoj[5c] suggested a Pd(II)/Pd(0) process for a direct alkoxylation of *N*-methoxybenzamides. These possible mechanisms should not be excluded.

Scheme 1. Plausible Reaction Mechanism



In summary, we have developed an efficient route for direct alkoxylation of aromatic azo compounds via a Pd-catalyzed azo group directed sp^2 C−H bond activation, in which $PhI(OAc)_2$ was found to be a particularly effective oxidant to these transformations and exhibited functional group tolerance. A series of azobenzene derivatives with either electron-donating or electron-withdrawing groups could be alkoxylated directly and efficiently. The method was applicable to both primary and secondary alcohols. This work provided a convenient method for the syntheses of 2-alkoxyl aromatic azo compounds from readily accessible starting materials under mild reaction conditions and therefore is an important extension of the chemistry of azo compounds.

Experimental Section

General

All reactions were run in a sealed tube with a Teflon lined cap under air atmosphere. Chemicals were commercially available and were used without purification. Aromatic azo compounds substrates were prepared according to the literature procedures.[12] ^{1}H NMR and ^{13}C NMR spectra were recorded in $CDCl_3$ [using $(CH_3)_4Si$ (for ^{1}H, δ = 0.00; for ^{13}C, δ = 77.00) as internal standard]. The following abbreviations were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet. Melting points are uncorrected. HRMS was obtained by ESI on TOF mass analyzer.

General Experimental Procedures and Characterizations

Azobenzene (0.5 mmol), alcohol (2 mL), $Pd(OAc)_2$ (0.05 mmol) and $PhI(OAc)_2$ (1.0 mmol) were added in a 25 mL sealed tube with a Teflon lined cap. The mixture was heated at 80 ^{o}C (oil bath temperature) for 24 h. After cooling to room temperature, the volatiles were removed under reduced pressure, and the residue was purified by a flash column chromatography on silica gel using hexane/ethyl acetate as eluent to give the corresponding product.

(E)-1-(2-Methoxyphenyl)-2-phenyldiazene **(3aa)**[13] Yield: 75% (79 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.95-7.93 (m, 2H), 7.70 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 1H), 7.55-7.45 (m, 4H), 7.12 (dd, J_1 = 8.0 Hz, J_2 = 0.6 Hz, 1H), 7.07-7.03 (m, 1H), 4.06 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 157.0, 153.2, 142.3, 132.5, 130.8, 129.0, 123.0, 120.8, 117.0, 112.7, 56.4.

(E)-1-(2-Ethoxyphenyl)-2-phenyldiazene **(3ab)** Yield: 63% (72 mg). Reddish orange oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.94 (d, J = 1.2 Hz, 2H), 7.69 (dd, J_1 = 8.0 Hz, J_2 = 2.0 Hz, 1H), 7.55-7.42 (m, 4H), 7.12 (dd, J_1 = 8.0 Hz, J_2 = 1.0 Hz, 1H), 7.06-7.02 (m, 1H), 4.29 (q, J = 6.8 Hz, 2H), 1.55 (t, J = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.5, 153.1, 142.6, 132.4, 130.7, 129.1, 123.0, 120.8, 117.0, 114.5, 65.3, 14.9. HRMS-ESI (m/z): calcd for $C_{14}H_{15}N_2O$ $[M + H]^+$ 227.1179, found 227.1168.

(E)-1-Phenyl-2-(2-propoxyphenyl)diazene **(3ac)** Yield: 77% (93 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.97-7.94 (m, 2H), 7.70 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 1H), 7.56-7.42 (m, 4H), 7.12 (dd, J_1 = 8.4 Hz, J_2 = 1.2 Hz, 1H), 7.06-7.02 (m, 1H), 4.20 (t, J = 6.4 Hz, 2H), 1.99-1.92 (m, 2H), 1.13 (t, J = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.7, 153.2, 142.7, 132.3, 130.7, 129.0, 123.0, 120.8, 117.0, 114.7, 71.3, 22.7, 10.6. HRMS-ESI (m/z): calcd for $C_{15}H_{17}N_2O$ $[M + H]^+$ 241.1341, found 241.1346.

(E)-1-(2-Isopropoxyphenyl)-2-phenyldiazene **(3ad)** Yield: 55% (66 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.94 (d, J = 1.2Hz, 2H), 7.69 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 1H), 7.56-7.48 (m, 3H), 7.44-7.40 (m, 1H), 7.14 (dd, J_1 = 8.0 Hz, J_2 = 1.0 Hz, 1H), 7.08-7.04 (m, 1H), 4.72 (m, 1H), 1.45 (d, J = 4.0 Hz, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.0, 153.1, 144.1, 132.1, 130.7, 129.0, 123.0, 121.5, 118.5, 117.1, 73.8, 22.3. HRMS-ESI (m/z): calcd for $C_{15}H_{17}N_2O$ $[M + H]^+$ 241.1341, found 241.1338.

(E)-1-(2-Butoxyphenyl)-2-phenyldiazene **(3ae)** Yield: 62% (79 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.96-7.94 (m, 2H), 7.70 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 1H), 7.56-7.42 (m, 4H), 7.12 (dd, J_1 = 8.4 Hz, J_2 = 0.8 Hz, 1H), 7.06-7.02 (m, 1H), 4.22 (t, J = 6.4 Hz, 2H), 1.96-1.89 (m, 2H), 1.64-1.55 (m, 2H), 1.04 (t, J = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.7, 153.2, 142.7, 132.3, 130.7, 129.0, 123.0, 120.8, 117.0, 114.7, 69.6, 31.4, 19.3, 13.9. HRMS-ESI (m/z): calcd for $C_{16}H_{19}N_2O$ $[M + H]^+$ 255.1497, found 255.1483.

(E)-1-(2-Isobutoxyphenyl)-2-phenyldiazene **(3af)** Yield: 65% (83 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.94 (d, J = 2.8 Hz, 2H), 7.70 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 1H), 7.56-7.41 (m, 4H), 7.11 (dd, J_1 = 8.4 Hz, J_2 = 0.8 Hz, 1H), 7.06-7.01 (m, 1H), 3.97 (d, J = 6.4 Hz, 2H), 2.29-2.22 (m, 1H), 1.12 (d, J = 6.4 Hz, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.8, 153.2, 142.7, 132.3, 130.6, 129.0, 123.0, 120.7, 117.0, 114.7, 76.1, 28.5, 19.3. HRMS-ESI (m/z): calcd for $C_{16}H_{19}N_2O$ $[M + H]^+$ 255.1497, found 255.1501.

(E)-1-(2-(Cyclopentyloxy)phenyl)-2-phenyldiazene **(3ag)** Yield: 52% (69 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.96-7.94 (m, 2H), 7.69 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 1H), 7.57-7.40 (m, 4H), 7.14-7.01 (m, 2H), 5.00 (t, J = 2.4 Hz, 1H), 2.08-1.87 (m, 6H), 1.69-1.62 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.9, 153.2, 143.5, 132.1, 130.6, 129.1, 123.0, 120.8, 117.0, 116.8, 81.8, 33.0, 24.0. HRMS-ESI (m/z): calcd for $C_{17}H_{19}N_2O$ $[M + H]^+$ 267.1497, found 267.1492.

(E)-1-(2-Methoxy-5-methylphenyl)-2-m-tolyldiazene **(3ba)** Yield: 69% (83 mg). Reddish orange solid, mp: 71-73 ^{o}C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.76-7.73 (m, 2H), 7.49 (d, J = 1.6 Hz, 1H), 7.41 (t, J = 8.0 Hz, 1H), 7.30-7.26 (m, 2H), 7.01 (d, J = 8.0 Hz, 1H), 4.03 (s, 3H), 2.47 (s, 3H), 2.37 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.0, 153.3, 142.0, 138.9, 132.9, 131.5, 130.3, 128.8, 122.6, 121.0,

117.2, 112.7, 56.5, 21.3, 20.5. HRMS-ESI (m/z): calcd for $C_{15}H_{17}N_2O$ $[M + H]^+$ 241.1341, found 241.1352.

(E)-1-(2-Ethoxy-5-methylphenyl)-2-m-tolyldiazene **(3bb)** Yield: 57% (72 mg). Orange solid, mp: 57-59 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.75 (d, J = 6.4 Hz, 2H), 7.48 (d, J = 1.6 Hz, 1H), 7.41 (t, J = 8.0 Hz, 1H), 7.30 (s, 1H), 7.24 (dd, J_1 = 8.4 Hz, J_2 = 2.0 Hz, 1H), 7.01 (d, J = 8.4 Hz, 1H), 4.26 (q, J = 6.8 Hz, 2H), 2.47 (s, 3H), 2.36 (s, 3H), 1.53 (t, J = 7.0 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 154.5, 153.2, 142.4, 138.9, 132.8, 131.5, 130.4, 128.8, 123.1, 120.6, 117.2, 114.8, 65.6, 21.4, 20.5, 14.9. HRMS-ESI (m/z): calcd for $C_{16}H_{18}N_2ONa$ $[M + Na]^+$ 277.1317, found 277.1333.

(E)-1-(5-Methyl-2-propoxyphenyl)-2-m-tolyldiazene **(3bc)** Yield: 70% (94 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.76-7.75 (m, 2H), 7.49 (d, J = 1.6 Hz, 1H), 7.43-7.39 (m, 1H), 7.30-7.23 (m, 2H), 7.02 (d, J = 8.4 Hz, 1H), 4.15 (t, J = 6.4 Hz, 2H), 2.48 (s, 3H), 2.36 (s, 3H), 1.96-1.91 (m, 2H), 1.11 (t, J = 7.6 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 154.7, 153.3, 142.5, 138.8, 132.8, 131.4, 130.4, 128.8, 123.2, 120.5, 117.2, 115.0, 71.7, 22.7, 21.4, 20.5, 10.5. HRMS-ESI (m/z): calcd for $C_{17}H_{21}N_2O$ $[M + H]^+$ 269.1648, found 269.1642.

(E)-1-(2-Isopropoxy-5-methylphenyl)-2-m-tolyldiazene **(3bd)** Yield: 51% (68 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.78-7.76 (m, 2H), 7.50 (d, J = 1.6 Hz, 1H), 7.45-7.40 (m, 1H), 7.31-7.29 (m, 1H), 7.25-7.22 (m, 1H), 7.05 (d, J = 8.0 Hz, 1H), 4.65 (m, 1H), 2.49 (s, 3H), 2.38 (s, 3H), 1.44 (d, J = 6.0 Hz, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 154.0, 153.2, 144.0, 138.9, 132.7, 131.5, 131.4, 128.8, 123.5, 120.3, 119.2, 117.2, 74.4, 22.3, 21.4, 20.6. HRMS-ESI (m/z): calcd for $C_{17}H_{21}N_2O$ $[M + H]^+$ 269.1648, found 269.1653.

(E)-1-(2-Isobutoxy-5-methylphenyl)-2-m-tolyldiazene **(3bf)** Yield: 67% (95 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.78-7.76 (m, 2H), 7.49 (d, J = 1.6 Hz, 1H), 7.44-7.40 (m, 1H), 7.30-7.29 (m, 1H), 7.25-7.23 (m, 1H), 7.01 (d, J = 8.4 Hz, 1H), 3.95 (d, J = 6.4 Hz, 2H), 2.48 (s, 3H), 2.37 (s, 3H), 2.29-2.19 (m, 1H), 1.11 (d, J = 6.8 Hz, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 154.9, 153.3, 142.5, 138.8, 132.8, 131.4, 130.3, 128.8, 123.4, 120.3, 117.1, 115.1, 76.6, 28.5, 21.4, 20.5, 19.3. HRMS-ESI (m/z): calcd for $C_{18}H_{23}N_2O$ $[M + H]^+$ 283.1805, found 283.1803.

(E)-1-(2-(Cyclopentyloxy)-5-methylphenyl)-2-m-tolyldiazene **(3bg)** Yield: 47% (69 mg). Red thick oil.

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.76-7.74 (m, 2H), 7.48-7.47 (m, 1H), 7.41 (t, *J* = 8.2 Hz, 1H), 7.30 (t, *J* = 0.4 Hz, 1H), 7.24-7.21 (m, 1H), 7.02 (d, *J* = 8.4 Hz, 1H), 4.95 (m, 1H), 2.48 (s, 3H), 2.36 (s, 3H), 2.04-2.02 (m, 2H), 1.95-1.89 (m, 4H), 1.66 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.8, 153.2, 143.4, 138.8, 132.7, 131.4, 130.5, 128.8, 123.4, 120.3, 117.3, 117.2, 82.3, 32.9, 23.9, 21.4, 20.5. HRMS-ESI (m/z): calcd for $C_{19}H_{23}N_2O$ $[M + H]^+$ 295.1810, found 295.1823.

(E)-1-(5-Chloro-2-methoxyphenyl)-2-(3-chlorophenyl)diazene **(3ca)** Yield: 62% (87 mg). Orange solid, mp:77-79 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.91-7.89 (m, 1H), 7.86-7.81 (m, 1H), 7.69 (d, *J* = 2.8 Hz, 1H), 7.49-7.42 (m, 3H), 7.05 (d, *J* = 8.8 Hz, 1H), 4.05 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.0, 153.6, 142.1, 135.2, 132.3, 130.9, 130.1, 126.5, 122.8, 121.8, 117.0, 114.1, 56.7. HRMS-ESI (m/z): calcd for $C_{13}H_{11}Cl_2N_2O$ $[M + H]^+$ 281.0248, found 281.0272.

(E)-1-(5-Chloro-2-ethoxyphenyl)-2-(3-chlorophenyl)diazene **(3cb)** Yield: 43% (63 mg). Orange solid, mp: 54-55 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.91-7.90 (m, 1H), 7.87-7.84 (m, 1H), 7.69 (d, *J* = 2.8 Hz, 1H), 7.48-7.45 (m, 2H), 7.40 (dd, J_1 = 8.8 Hz, J_2 = 2.4 Hz, 1H), 7.05 (d, *J* = 9.2 Hz, 1H), 4.30 (q, *J* = 7.2 Hz, 2H), 1.55 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.5, 153.6, 142.4, 135.1, 132.2, 130.9, 130.1, 126.5, 122.6, 122.0, 117.0, 115.8, 65.7, 14.8. HRMS-ESI (m/z): calcd for $C_{14}H_{13}Cl_2N_2O$ $[M + H]^+$ 295.0405, found 295.0418.

(E)-1-(5-Chloro-2-propoxyphenyl)-2-(3-chlorophenyl)diazene **(3cc)** Yield: 59% (91 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.90 (d, *J* = 1.2 Hz, 1H), 7.86-7.83 (m, 1H), 7.68 (d, *J* = 2.4 Hz, 1H), 7.48-7.46 (m, 2H), 7.40 (dd, J_1 = 8.8 Hz, J_2 = 2.4 Hz, 1H), 7.05 (d, *J* = 8.8 Hz, 1H), 4.16 (t, *d* = 6.4 Hz, 2H), 1.94 (m, 2H), 1.12 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.7, 153.6, 142.5, 135.1, 132.0, 130.9, 130.1, 126.5, 122.5, 122.1, 117.0, 115.9, 71.6, 22.6, 10.5. HRMS-ESI (m/z): calcd for $C_{15}H_{15}Cl_2N_2O$ $[M + H]^+$ 309.0561, found 309.0567.

(E)-1-(5-Chloro-2-isopropoxyphenyl)-2-(3-chlorophenyl)diazene **(3cd)** Yield: 35% (54 mg). Orange solid, mp: 50-52 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.91-7.90 (m, 1H), 7.86-7.83 (m, 1H), 7.68 (d, *J* = 2.4 Hz, 1H), 7.50-7.45 (m, 2H), 7.39 (dd, J_1 = 8.4 Hz, J_2 = 2.4 Hz, 1H), 7.06 (d, *J* = 5.6 Hz, 1H), 4.70 (m, 1H), 1.45 (d, *J* = 6.0 Hz, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 154.9, 153.6, 143.8, 135.1, 132.1, 130.9, 130.1, 127.1, 122.6, 122.2, 119.4, 117.1, 74.1, 22.2. HRMS-ESI (m/z): calcd for $C_{15}H_{15}Cl_2N_2O$

$[M + H]^+$ 309.0561, found 309.0566.

(E)-1-(5-Bromo-2-methoxyphenyl)-2-(3-bromophenyl)diazene **(3da)** Yield: 66% (122 mg). Orange solid, mp: 140-142 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.05 (t, *J* = 2.0 Hz, 1H), 7.91-7.88 (m, 1H), 7.81 (d, *J* = 2.4 Hz, 1H), 7.63-7.56 (m, 2H), 7.42 (t, *J* = 8.0 Hz, 1H), 7.01 (d, *J* = 8.8 Hz, 1H), 4.05 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.4, 153.7, 142.4, 135.2, 133.9, 130.5, 124.6, 123.4, 123.2, 120.0, 114.6, 113.8, 56.6. HRMS-ESI (m/z): calcd for $C_{13}H_{11}Br_2N_2O$ $[M + H]^+$ 370.9218, found 370.9240.

(E)-1-(5-Bromo-2-ethoxyphenyl)-2-(3-bromophenyl)diazene **(3db)** Yield: 47% (90 mg). Orange solid, mp: 77-79 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.06 (t, *J* = 2.0 Hz, 1H), 7.91-7.88 (m, 1H), 7.81 (d, *J* = 2.4 Hz, 1H), 7.63-7.60 (m, 1H), 7.56-7.53 (m, 1H), 7.42 (t, *J* = 8.0 Hz, 1H), 7.00 (d, *J* = 8.8 Hz, 1H), 4.27 (q, *J* = 6.8 Hz, 2H), 1.55 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.9, 153.7, 142.7, 135.1, 133.8, 130.4, 125.0, 123.2, 123.1, 120.0, 116.2, 113.8, 65.6, 14.8. HRMS-ESI (m/z): calcd for $C_{14}H_{13}Br_2N_2O$ $[M + H]^+$ 384.9374, found 384.9377.

(E)-1-(5-Bromo-2-propoxyphenyl)-2-(3-bromophenyl)diazene **(3dc)** Yield: 65% (129 mg). Orange solid, mp: 55-57 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.06 (t, *J* = 2.0 Hz, 1H), 7.90-7.88 (m, 1H), 7.81 (d, *J* = 2.4 Hz, 1H), 7.63-7.60 (m, 1H), 7.53 (dd, J_1 = 8.8 Hz, J_2 = 2.8 Hz, 1H), 7.41 (t, *J* = 8.0 Hz, 1H), 7.00 (d, *J* = 8.8 Hz, 1H), 4.15 (t, *J* = 6.4 Hz, 2H), 1.94 (m, 2H), 1.12 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.1, 153.7, 142.8, 135.1, 133.8, 130.4, 125.1, 123.1, 123.0, 120.0, 116.3, 113.7, 71.6, 22.6, 10.4. HRMS-ESI (m/z): calcd for $C_{15}H_{15}Br_2N_2O$ $[M + H]^+$ 398.9531, found 398.9515.

(E)-1-(5-Bromo-2-isopropoxyphenyl)-2-(3-bromophenyl)diazene **(3dd)** Yield: 40% (79 mg). Orange solid, mp: 62-64 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.06 (t, *J* = 2.0 Hz, 1H), 7.90-7.88 (m, 1H), 7.81 (d, *J* = 2.4 Hz, 1H), 7.63-7.60 (m, 1H), 7.53 (dd, J_1 = 8.8 Hz, J_2 = 2.8 Hz, 1H), 7.42 (t, *J* = 8.0 Hz, 1H), 7.03 (d, *J* = 8.8 Hz, 1H), 4.69 (m, 1H), 1.45 (d, *J* = 6.0 Hz, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.4, 153.7, 144.0, 135.0, 133.8, 130.4, 125.1, 123.1, 123.0, 120.1, 119.7, 114.3, 74.0, 22.6, 22.2. HRMS-ESI (m/z): calcd for $C_{15}H_{15}Br_2N_2O$ $[M + H]^+$ 398.9531, found 398.9542.

(E)-1-(2-Ethoxy-5-methoxyphenyl)-2-(3-methoxyphenyl)diazene **(3eb)** Yield: 55% (79 mg). Red thick

oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.61-7.58 (m, 1H), 7.49 (t, *J* = 2.4 Hz, 1H), 7.44 (t, *J* = 8.0 Hz, 1H), 7.29 (t, *J* = 2.8 Hz, 1H), 7.08-7.03 (m, 3H), 4.25 (q, *J* = 6.8 Hz, 2H), 3.92 (s, 3H), 3.86 (s, 3H), 1.51 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 160.3, 154.3, 151.5, 142.9, 129.7, 119.6, 117.6, 117.3, 117.1, 106.2, 100.4, 66.9, 55.8, 55.4, 15.1. HRMS-ESI (m/z): calcd for $C_{16}H_{19}N_2O_3$ $[M + H]^+$ 287.1396, found 287.1401.

(E)-1-(5-Methoxy-2-propoxyphenyl)-2-(3-methoxyphenyl)diazene **(3ec)** Yield: 51% (76 mg). Red thick oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.61-7.58 (m, 1H), 7.50 (t, *J* = 2.4 Hz, 1H), 7.47-7.42 (m, 1H), 7.29 (t, *J* = 2.8 Hz, 1H), 7.09-7.00 (m, 3H), 4.14 (t, *J* = 6.4 Hz, 2H), 3.91 (s, 3H), 3.86 (s, 3H), 1.91-1.90 (m, 2H), 1.11 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 160.3, 154.3, 154.2, 151.8, 142.9, 129.7, 119.6, 117.7, 117.4, 117.3, 105.7, 100.3, 72.9, 55.8, 55.4, 22.9, 10.6. HRMS-ESI (m/z): calcd for $C_{17}H_{21}N_2O_3$ $[M + H]^+$ 301.1552, found 301.1556.

(E)-1-(5-Acetyl-2-methoxyphenyl)-2-(3-acetylphenyl)diazene **(3fa)** Yield: 42% (62 mg). Orange solid, mp: 129-131 °C. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.50 (t, *J* = 2.0 Hz, 1H), 8.27 (d, *J* = 2.0 Hz, 1H), 8.17-8.09 (m, 3H), 7.64 (t, *J* = 8.0 Hz, 1H), 7.19 (d, *J* = 8.8 Hz, 1H), 4.13 (s, 3H), 2.72 (s, 3H), 2.65 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 197.5, 196.7, 160.5, 153.0, 141.4, 138.2, 132.8, 130.5, 130.1, 129.5, 126.8, 123.6, 117.6, 112.5, 56.6, 26.8, 26.5. HRMS-ESI (m/z): calcd for $C_{17}H_{17}N_2O_3$ $[M + H]^+$ 297.1239, found 297.1243.

ASSOCIATED CONTENT

Supporting Information

Copies of ^{1}H NMR and ^{13}C NMR spectra for all products. 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.

■ ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Project 21272117 and 20972068) and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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