methods: $RuX_2PR_3(\eta^6$-arene), ref 23; $(RuCl_2$(norbornadiene))$_n$, ref 27; $RuCl_2$(pyridine)$_2$(norbornadiene), ref 25; $RuH_2(PPh_3)_4$, ref 21; $Ru(\eta^5$-$C_5H_5)Cl(PPh_3)_2$, ref 22; $[Ru(\eta^6$-$C_6H_6)(\eta^4$-$C_6H_8)]$, ref 26; $Ru_3(CO)_{12}$, ref 28; $HRu_3(CO)_{11}NEt_4$, ref 19; and $RuCo(CO)_7(\mu$-$PPh_2)$, ref 20.

Addition to Terminal Alkynes. In a typical run, solvent (10 mL), secondary amine (20 mmol), alkyne (10 mmol), and ruthenium complex (0.2 mmol) were placed in a 125-mL stainless steel autoclave. Carbon dioxide was used first to flush out the reactor and then to pressurize it to the starting pressure (5 MPa). The reaction mixture was stirred at 100–140 °C for 20 h. After cooling, the autoclave was washed with solvent and the solution concentrated to about 10 mL. The enol carbamates were analyzed by VPC using hexamethylbenzene or triphenylmethane as internal standard. After elimination of the solvent, organic compounds (carbamates and enynes) were collected under reduced pressure. Thick layer chromatography of these products with a dichloromethane–petroleum ether mixture (1/1) as eluent gave a good separation of the enol carbamates from the enynes.

(*Z*)-β-[(Diethylcarbamoyl)oxy]styrene (1A(a)): ^{1}H NMR (C_6D_6, 300 MHz) δ 7.56 (d, 1, J = 7.5 Hz, =CHO), 7.4 (m, 5, Ph), 5.44 (d, 1, J = 7.5 Hz, =CHPh), 3.06 (q, 2, J = 7 Hz, NCH_2), 2.95 (q, 2, J = 7 Hz, NCH_2), 0.90 (t, 3, J = 7 Hz, CH_3), 0.84 (t, 3, J = 7 Hz, CH_3); IR (neat) ν 1730 (C=O), 1660 (C=C) cm^{-1}; MS m/z 219.126 (M^+).

(*E*)-β-[(Diethylcarbamoyl)oxy]styrene (2A(a)): ^{1}H NMR (C_6D_6, 300 MHz) δ 8.16 (d, 1, J = 12.9 Hz, =CHO), 7.4 (m, 5, Ph), 6.27 (d, 1, J = 12.9 Hz, =CHPh), 3.06 (q, 2, J = 7 Hz, NCH_2), 2.95 (q, 2, J = 7 Hz, NCH_2), 0.90 (t, 3, J = 7 Hz, CH_3), 0.84 (t, 3, J = 7 Hz, CH_3); IR (neat) ν 1730 (C=O), 1660 (C=C) cm^{-1}; MS m/z 219.126 (M^+).

(*Z*)-1-[(Diethylcarbamoyl)oxy]hex-1-ene (1A(b)): ^{1}H NMR (C_6D_6, 100 MHz) δ 6.96 (d, 1, J = 6 Hz, =CHO), 4.74 (dt, 1, $J_{CH=CH}$ = 6 Hz, J_{CH_2-CH} = 6 Hz, $CHCH_2$), 3.33 (q, 2, J = 7 Hz, NCH_2, 2.13 (m, 2, CH_2), 1.38 (m, 4, CH_2), 1.18 (t, 6, J = 7 Hz, CH_3CH_2N), 0.90 (t, 3, J = 6 Hz, $CH_3(CH_2)_3$); IR (neat) ν 1720 (C=O), 1670 (C=C) cm^{-1}; MS m/z 199.157 (M^+).

(*E*)-1-[(Diethylcarbamoyl)oxy]hex-1-ene (2A(b)): ^{1}H NMR (C_6D_6, 100 MHz) δ 6.92 (d, 1, J = 14 Hz, =CHO), 5.22 (dt, 1, $J_{CH=CH}$ = 14 Hz, J_{CH_2-CH} = 7 Hz, $=CHCH_2$), 3.30 (q, 4, J = 6 Hz, NCH_2), 1.34 (m, 2, CH_2), 1.20 (m, 4, CH_2), 1.14 (t, 6, J = 6 Hz, CH_3CH_2N), 0.88 (t, 3, J = 6 Hz, $CH_3(CH_2)_3$); IR (neat) ν 1720 (C=O), 1675 (C=C) cm^{-1}; MS m/z 199.157 (M^+).

(*Z*)-β-[(Dimethylcarbamoyl)oxy]styrene (1B(a)): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.47 (d, 1, J = 8 Hz, =CHO), 7.2–7.35 (m, 5, Ph), 5.55 (d, 1, J = 8 Hz, =CHPh), 3.07 (s, 3, CH_3), 3.00 (s, 3, CH_3); IR (neat) ν 1730 (C=O), 1665 (C=C) cm^{-1}; MS m/z 191.095 (M^+).

(*E*)-β-[(Dimethylcarbamoyl)oxy]styrene (2B(a)): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.72 (d, 1, J = 13 Hz, =CHO), 7.20–7.35 (m, 5, Ph), 6.24 (d, 1, J = 13 Hz, =CHPh), 3.07 (s, 3, CH_3), 3.00 (s, 3, CH_3); IR (neat) ν 1730 (C=O), 1665 (C=C) cm^{-1}; MS m/z 191.095 (M^+).

(*Z*)-β-[(Piperidinocarbamoyl)oxy]styrene (1C(a)): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.15–7.25 (m, 5, Ph), 7.15 (d, 1, J = 9 Hz, =CHO), 5.48 (d, 1, J = 9 Hz, =CHPh), 3.51 (m, 4, CH_2N), 1.51 (m, 6, CH_2); IR (neat) ν 1725 (C=O), 1660 (C=C) cm^{-1}; MS m/z 231.126 (M^+).

(*Z*)-β-[(Morpholinocarbamoyl)oxy]styrene (1D(a)): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.2 (m, 5, Ph, =CHO masked), 5.55 (d, 1, J = 8 Hz, =CHPh), 3.62 (m, 4, OCH_2), 1.24 (m, 4, NCH_2); IR (neat) ν 1725 (C=O), 1660 (C=C) cm^{-1}; MS m/z 233.105 (M^+).

(*Z*)-β-[(Methylbutylcarbamoyl)oxy]styrene (1E(a)): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.0–7.6 (m, 5, Ph), 7.6 (d, 1, J = 7 Hz, =CHO), 5.44 (d, 1, J = 7 Hz, =CHPh), 3.05 (t, 2, J = 7 Hz, NCH_2), 2.49 (s, 3, NCH_3), 1.30 (m, 4, CH_2), 0.79 (t, 3, J = 7 Hz, CH_3); IR (neat) ν 1725 (C=O), 1665 (C=C) cm^{-1}; MS m/z 233.141 (M^+).

(*E*)-β-[(Methylbutylcarbamoyl)oxy]styrene (2E(a)): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 8.20 (d, 1, J = 13 Hz, =CHO), 7.0–7.6 (m, 5, Ph), 6.31 (d, 1, J = 13 Hz, =CHPh), 2.89 (t, 2, J = 7 Hz, NCH_2), 2.49 (s, 3, CH_3N), 1.3 (m, 4, CH_2), 0.73 (t, 3, J = 7 Hz, CH_3); IR (neat) ν 1720 (C=O), 1660 (C=C) cm^{-1}; MS m/z 233.141 (M^+).

Addition to Acetylene. Secondary amine (100 mmol), ruthenium complex (2 mmol), and acetonitrile (50 mL) were first placed in the autoclave. Acetylene (320 mmol) was dissolved in the solvent under atmospheric pressure after cooling the autoclave to −50 °C. An excess of acetylene in the ratio acetylene/amine of about 3 was necessary. The reactor was then stirred under CO_2 pressure (1.5–2 MPa) at 80–100 °C for 20 h. The analysis of the reaction mixture was similar to that described above in the case of terminal alkynes.

[(Diethylcarbamoyl)oxy]ethylene (4A): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.2 (dd, 1, J_{cis} = 6.5 Hz, J_{trans} = 15 Hz, =CHO), 4.70 (d, 1, J_{trans} = 15 Hz, $=CH_2$), 4.40 (d, 1, J_{cis} = 6.5 Hz, $=CH_2$), 3.3 (q, 4, J = 7 Hz, NCH_2), 1.1 (t, 6, J = 7 Hz, CH_3); IR (neat) ν 1720 (C=O), 1650 (C=C) cm^{-1}.

[(Piperidinocarbamoyl)oxy]ethylene (4C): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.27 (dd, 1, J_{cis} = 6.5 Hz, J_{trans} = 15 Hz, =CHO), 4.76 (d, 1, J_{trans} = 15 Hz, $=CH_2$), 4.44 (d, 1, J_{cis} = 6.5 Hz, $=CH_2$), 3.47 (m, 4, CH_2N), 1.60 (m, 6, CH_2); IR (neat) ν 1715 (C=O), 1650 (C=C) cm^{-1}.

[(Morpholinocarbamoyl)oxy]ethylene (4D): ^{1}H NMR (CCl_4, 100 MHz) δ 7.21 (dd, 1, J_{cis} = 6.5 Hz, J_{trans} = 15 Hz, =CHO), 4.72 (d, 1, J_{trans} = 15 Hz, $=CH_2$), 4.42 (d, 1, J_{cis} = 6.5 Hz, $=CH_2$), 3.55 (m, 8, CH_2); IR (neat) ν 1720 (C=O), 1640 (C=C) cm^{-1}.

[(Pyrrolidinocarbamoyl)oxy]ethylene (4F): ^{1}H NMR ($CDCl_3$, 100 MHz) δ 7.20 (dd, 1, J_{cis} = 6 Hz, J_{trans} = 14 Hz, =CHO), 4.70 (d, 1, J_{trans} = 14 Hz, $=CH_2$), 4.33 (d, 1, J_{cis} = 6 Hz, $=CH_2$), 3.37 (m, 4, CH_2N), 1.80 (m, 4, CH_2); IR (neat) ν 1720 (C=O), 1640 (C=C) cm^{-1}.

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Transition Metal Catalyzed Grignard Cross-Coupling to Ortho-Halogenated Aryl Imines. An Efficient Synthesis of Ortho-Substituted Aryl Aldehydes

Lendon N. Pridgen,* L. Snyder,[1a] and J. Prol, Jr.[1b]

Division of Chemical Research & Development, Smith Kline & French Laboratories, P.O. Box 1539, King of Prussia, Pennsylvania 19406-0939

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N-(*o*-Halogenated benzylidene)cyclohexylamines **2** were successfully reacted with reducing and nonreducing Grignard reagents in a transition metal catalyzed cross-coupling reaction resulting in an efficient single-step synthesis of ortho-substituted benzaldehydes after acidic workup. The dihalogenated benzylidene amines reacted regioselectively at the imine-activated ortho position to yield ortho-substituted halogenated benzaldehydes.

Although various synthesis of aromatic aldehydes have been reported,[2] none filled our particular requirements for an efficient synthesis of an ortho-substituted benzaldehyde intermediate in the synthesis of a pharmacologically active

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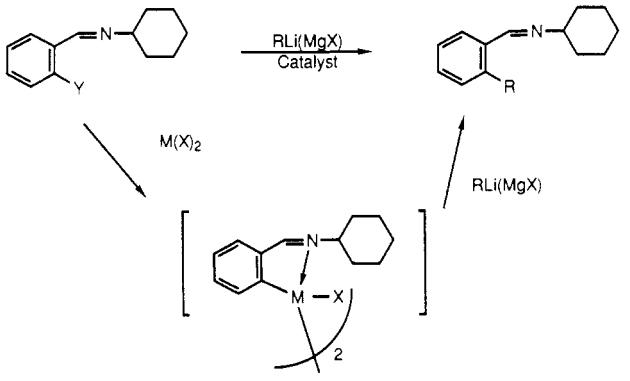
Table I. Nickel and Iron Acetylacetonoate Catalyzed Cross-Coupling Reaction of Grignard Reagents to *N*-(*o*-Halogenated benzylidene)cyclohexylamine 2

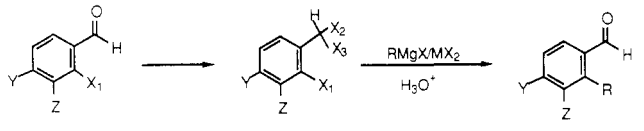
entry	3 (Y = Z = H), R =	% yield[a]	MS *m/e*	IR, cm^{-1}	^1H NMR ($CDCl_3$), δ
1	**a**: CH_2TMS	90	calcd for $C_{11}H_{16}OSi$ (M^+) 192.0970, found *m/e* 192.0965	1700	10.2 (s, 1 H), 7.8–6.9 (m, 4 H), 2.6 (s, 2 H), 0.0 (s, 9 H)
2	**b**: Ph	92[b]	182	1700	10.0 (s, 1 H), 8.1–7.3 (m, 9 H)
3	**c**: CH_2Ph	52	calcd for $C_{14}H_{12}O$ (M^+) 196.0888, found *m/e* 196.081	1700	10.1 (s, 1 H), 8.7–6.8 (m, 9 H), 4.3 (s, 2 H)
4	**d**: CH_3	77[b]	120	1700	10.2 (s, 1 H), 7.8–7.0 (m, 4 H), 2.6 (s, 3 H)
5	**e**: *n*-C_4H_9	85[b,c]	162	1700	10.3 (s, 1 H), 8.0–7.1 (m, 4 H), 3.0 (t, 2 H), 2.0–0.7 (m, 7 H)
6	**f**: $CH{=}CH_2$	36[d] (40)[e]	calcd for C_9H_8O (M^+) 132.0575, found *m/e* 132.0575	1700	10.3 (s, 1 H), 7.9–7.1 (m, 4 H), 5.3–5.8 (m, 3 H)
7	**g**: *m*-CH_3	nr			
8	**h**: C≡CPh	nr			
9	**i**:[f] CH_2TMS	91	calcd for $C_{11}H_{15}ClOSi$ (M^+) 226.0580, found *m/e* 226.0580	1680	10.0 (s, 1 H), 7.7–6.9 (m, 3 H), 2.7 (s, 9 H)
10	**j**:[f] CH_3	61	calcd for C_8H_7ClO (M^+) 154.0185, found *m/e* 154.079	1680	10.15, (s, 1 H), 7.8–7.1 (m, 3 H), 2.6 (s, 3 H)

[a] Yields are unoptimized isolated yields. $Ni(AcAc)_2$ was used as catalyst (≃4 mol %) except where noted. The ratio of materials employed was chloro imine/Grignard/catalyst (1.0/1.4/0.04). [b] Compared to an authentic sample synthesized by reported methods or commercially obtained. [c] $Fe(AcAc)_3$ was used as catalyst. [d] Represents a 6:1 ratio of **3f** and benzaldehyde obtained with 4 mol % of 1:1 cuprous cyanide, $Ni(AcAc)_2$, and 3 equiv of vinyl Grignard. [e] Represents a 1.2:1 ratio of **3f** and benzaldehyde obtained with 8 mol % of 1:1 CuCN, $Ni(AcAc)_2$, and 3 equiv of vinyl Grignard. [f] **3** (Y = Cl, Z = H).

Scheme I



Scheme II



1a, X_1=Br, Y=Z=H
b, X_1=Cl, Y=Z=H
c, X_1=Y=Cl, Z=H
d, X_1=Y=H, Z=Cl

2a, Y=Z=H, X_1=Cl, X_2=X_3=NC_6H_{11}
b, Y=Z=H, X_1=Br, X_2=X_3=-O-$(CH_2)_3$-O-
c, Y=Z=H, X_1=Br, X_2=X_3=N-$(CH_2$-N-$CH_3)_2$ CH_3
d, Y=X_1=Cl, Z=H, X_2=X_3=OEt
e, Y=X_1=Cl, Z=H, X_2=X_3=-O-$(CH_2)_3$-O-
f, Y=X_1=Cl, Z=H, X_2=X_3=NC_6H_{11}
g, Y=X_1=H, Z=Cl, X_2=X_3=NC_6H_{11}

3(a-j, Table I)

compound. This laboratory required kilogram quantities of such an aldehyde and devoted considerable attention to this issue. Currently, the most general and chemically expedient approach to these aldehydes utilizes the chemistry developed in the Meyer's laboratory wherein a nucleophilic organometallic reagent displaces the activated methoxy of a 2-(*o*-methoxyphenyl)-4,4-dimethyl-2-oxazoline.[3] However, because several steps, albeit simple ones, are involved in carrying out this sequence, our effort focused on developing a simpler alternative strategy.

It appeared to us that a most desirable approach would start with a halogenated aryl aldehyde and be comprised simply of three steps: aldehyde protection, halogen replacement by the desired substituent, and deprotection. In a practical sense, these steps should not require refrigeration below −40 °C. Simple ortho metalation or metal halogen exchange on the suitably protected aldehyde (or its "equivalent") followed by electrophilic trapping would in many cases be sufficient. However, such an approach is only suitable for aliphatic electrophiles or certain other highly electropositive functionalities,[4,5] more often than not at low temperatures (<−40 °C).

The literature contains many examples of the reactivity of cyclopalladation products derived from 2-aryl imines and amines with palladium salts. These resulting σ-bonded aromatic palladium complexes may be reacted with other organometallic compounds, acetylenes, and olefins to yield 2-substituted imines, amines, and heterocycles. Unfortunately a stoichiometric quantity of palladium is required.[6]

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It occurred to us that these cyclopalladated or any other cyclometalated complexes would also be intermediates in a cross-coupling reaction between an organometallic and a 2-halogenated aryl imine catalyzed by a transition metal (Scheme I). However, the literature also reports that imines are generally too reactive to serve as protecting groups.[7] In fact we have found only a limited application of their use in a transition metal catalyzed cross-coupling reaction, the Ullman reaction.[8] We nevertheless decided to explore the tolerance of imines in a transition metal catalyzed cross-coupling reaction with Grignards since their ease of synthesis and hydrolysis would satisfy our criteria for the most desirable approach to ortho-substituted aryl aldehydes.

We found *N*-(*o*-halogenated benzylidene)cyclohexylamines **2a** and **2f** to be highly reactive in cross-coupling with Grignard reagents at ambient temperature in the presence of ≃4 mol % anhydrous nickel acetylacetonoate [$Ni(AcAc)_2$].[9] After the reaction mixture was quenched with 10% HCl or chromatographed over silica gel, the ortho-substituted aryl aldehyde was obtained in usually good to excellent yields (Table I, Scheme II). Alternatively, the precursor imine may be isolated directly by quenching the reaction mixture with only water. In this report our yields are based on conversion of the halogenated imine to the ortho-substituted aryl aldehyde.

Nonreducing Grignards, i.e., those that do not possess β-hydrogens, are most suitable in this coupling reaction. For $Ni(AcAc)_2$-catalyzed cases involving reducing Grignards, imine reduction products predominated. For example, reaction of ethyl Grignard with *N*-(*o*-chlorobenzylidene)cyclohexylamine (**2a**) gave a mixture of 80.4% *N*-[(*o*-ethylphenyl)methyl]cyclohexylamine (**4**), 18.9% *N*-(phenylmethyl)cyclohexylamine (**5**), and 0.7% unknown material as determined by GC/MS. This result was not entirely unexpected since the reduction of imines by Ni(0)-catalyzed Grignard cross-coupling reactions has been reported, as well as the propensity of nickel and palladium to facilitate β-hydride elimination of aliphatic Grignards.[10] However, by changing catalyst to iron acetylacetonoate [$Fe(AcAc)_3$],[11] we obtained a much better improved yield for the coupling reaction. Now reaction of ethyl Grignard with **2a** gave 61.2% of the desired *N*-(*o*-ethylbenzylidene)cyclohexylamine (**6**), 22.8% of **4**, and 16% of several dehalogenated products. *n*-Butyl Grignard was better yet (entry 5), yielding 85% *o*-*n*-butylbenzaldehyde and 8% benzaldehyde on acidic hydrolysis.

Without a catalyst the cross-coupling reaction did not occur, and both starting materials were returned. A variety of palladium catalysts were tried but were found to be much less effective in this system, yielding only about 4% product under the standard reaction conditions. All attempts to cross-couple acetylenic Grignards to **2a** were unsuccessful even though a variety of other substrates have been previously used satisfactorily with such Grignards.[12] Allyl Grignards under a variety of conditions with **2a** would only give *N*-[1-(2-propenyl)-1-(*o*-chlorophenyl)methyl]-cyclohexylamine (**7**) without any detection of cross-coupled material.[13] With **2c**, starting material was returned. Vinyl Grignard was cross-coupled in 40% yield with **2a** but only after use of a 1:1 combination of CuCN and $Ni(AcAc)_2$.[14] The major byproduct in this case was benzaldehyde, resulting from dechlorination of **2a**. *tert*-Butyl Grignard was ineffective in this coupling reaction, even after employing the Bell cross-coupling conditions.[14a]

Some other suitable protecting groups, primarily because of their stability and ease of hydrolysis, for this reaction were the 1,3-dioxanyl **2b** and *N*,*N*-dimethyl-1,2-dihydrodiazolinyl (**2c**)[4c] moieties.[15] However, *only the imine group facilitated cross-coupling in the dihalogenated series* (entries 9 and 10), *reacting regioselectively at the ortho position*. The diethoxy acetal **2d** and 1,3-dioxanyl **2e** protected dichloroaldehydes returned starting material. Undoubtedly, the inductive and/or chelating abilities of the imine group plays a major role in activating the ortho halogen toward cross-coupling. This conclusion is further substantiated by the failure of **2g**, the meta analogue of **2a**, to react with either the highly reactive methyl or (trimethylsilyl)methyl Grignard.

Thus with the high yield obtained for the Grignard cross-coupling of the ortho-halogenated benzylidene imines in Table I, we have demonstrated how our procedure is complementary to existing synthesis methods for ortho-substituted aromatic aldehydes.[2] *Additionally, we have also shown how the imine group is not only tolerant to but imparts exceptional reactivity toward Grignard cross-coupling of an adjacent halogen.* This regioselectivity should prove to be a useful tool in developing other synthesis strategies.

Experimental Section

All commercially obtained solvents and reagents were used without further purification. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl under a nitrogen atmosphere. Flash chromatography was done on "Baker silica gel for flash columns" (≃40 μm average particle diameter). Gas chromatography (GC) was performed on a Carlo-Erba capillary gas chromatograph Model FV4160-2 with use of a DB-1, 15 m × 0.252 mm capillary column. GC/MS were conducted on either a HP5790A with a mass selector detector with a DB-1 (30 m × 0.252 mm) column or a Finnigan-MAT Model 4610 quadrupole GC/MS using a 15 m × 0.25 mm DB-17 column.

IR spectra were taken on a Perkin-Elmer 283 instrument. High-resolution mass spectra were measured on a Varian MAT-CH5 double-focusing spectrometer. ^1H NMR spectra were taken on a Varian EM-360L with Me_4Si as internal standard.

All metal catalysts used in this study were purchased from Strem Chemicals, Inc.

Starting Materials. The halogenated aldehydes: *o*-bromobenzaldehyde (**1a**), *o*-chlorobenzaldehyde (**1b**), 2,4-dichlorobenzaldehyde (**1c**), and *m*-chlorobenzaldehyde (**1d**) were purchased from Aldrich. Aldehyde **1** were all converted to their respective protecting groups by known literature methods.[7,4c]

General Procedure for Cross-Coupling Grignard Reagents to *N*-(*o*-Halogenated benzylidene)cyclohexylamines (Table

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I). An oven-heated 100-mL three-necked flask containing a magnetic stirring bar was fitted with gas inlet and outlet tubes (the outlet connected to a gas bubbler containing silicon oil) and then was swept with nitrogen. After the apparatus cooled, 40 mL of THF per gram of protected aldehyde along with 2–8 mol % of catalyst (≃40 mg per gram of substrate) was added. The flask was then fitted with a neoprene septum, and the Grignard reagent (1.4 equiv) was added at 0 °C (73 °C for $Fe(AcAc)_3$-catalyzed examples). The reaction mixture was stirred at ambient temperature under nitrogen for 16 h and then poured onto 50 mL of 10% hydrochloric acid. If isolation of the imine is desired, the reaction should be poured onto water only. The organic layer was removed, and the aqueous layer was extracted several times with ether. The combined and dried ($MgSO_4$) ether layers were concentrated to an oil, which may be further purified by radial or flash chromatography.

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Mediated Electrochemical Synthesis of Aromatic Aldehydes, Ketones, and Quinones Using Ceric Methanesulfonate

Robert P. Kreh,* Robert M. Spotnitz, and Joseph T. Lundquist

W. R. Grace & Company, Washington Research Center, Columbia, Maryland 21044

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Cerium(IV) in aqueous methanesulfonic acid is an excellent reagent for the oxidation of alkyl aromatics and polycyclic aromatics to aldehydes, ketones, and quinones. The benefits of methanesulfonic acid include low cost, low nucleophilicity, stability to anodic and electrochemical oxidation, and high solubility of Ce(III) and Ce(IV) in aqueous solutions of this acid. The properties of this medium are ideal for electrochemical regeneration, giving current efficiencies up to 89% at 500 mA/cm^2. With this system, enhanced yields of menadione were obtained by adding Cr(VI). A new solid oxidant, $Ce(CH_3SO_3)_2(OH)_2 \cdot H_2O$, was produced electrochemically, providing a convenient starting material for these oxidations. Improved selectivity was obtained in the synthesis of *m*-phenoxybenzaldehyde by using this solid material in place of soluble Ce(IV).

Aromatic aldehydes, ketones, and quinones are important chemicals, with applications such as chemical intermediates, pharmaceuticals, agricultural chemicals, pulp and paper chemicals, dyestuffs, and flavor and fragrance materials. The preparation of these partially oxidized chemicals has generally relied on the high selectivity of transition metal oxidants such as chromium(VI),[1] manganese(III),[2] cobalt(III),[3] and cerium(IV).[4,5] The stoichiometric use and disposal of these reagents is undesirable from economic and environmental viewpoints. As a result, there has been much recent interest in the electrochemical recycle of these oxidants.[6]

Mediated, or indirect, electrosynthesis is a cyclic process involving electrochemical generation of a redox agent and use of that agent to effect a chemical reaction. Figure 1 shows the general scheme. A redox agent such as Ce(IV), generated in an electrochemical cell, is contacted with reactant in a conventional chemical reactor to form a product. The spent redox agent is separated from the product and returned to the electrochemical cells. Carrying out the chemical reaction and electrochemical reaction in separate vessels allows each reaction to be independently optimized. Pichaichanarong et al. have recently reviewed engineering aspects of mediated electrosynthesis.[7]

Of the above metal oxidants, chromium(VI) is the most soluble and has the lowest reduction potential and is thus the easiest to regenerate electrochemically. On the other hand, Cr(VI) generally gives the lowest selectivities in the organic oxidations of interest.[8-11] The manganic ion gives good selectivities but is unstable toward disproportionation, except at very high acid concentrations where both Mn(III) and Mn(II) have low solubilities.[10,12] The powerful Co(III) ion is also unstable, due to water oxidation.[3] Cerium(IV) is generally the reagent of choice due to its higher stability and solubility at acid concentrations, which yield excellent selectivities to aromatic carbonyl products.[4-11]

The usefulness of cerium(IV), particularly in indirect electrochemical oxidations, has been limited by the counteranions. Problems include instability toward oxidation (e.g., benzenesulfonate[13] and chloride[14]), reactivity with organic substrates (e.g., nitrate,[15] chloride,[14] and perchlorate[16]), or marginal solubility (e.g., sulfate,[17] acetate,[18]

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