

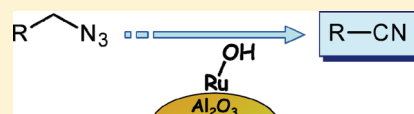
# Aerobic Oxidative Transformation of Primary Azides to Nitriles by Ruthenium Hydroxide Catalyst

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Supporting Information

**ABSTRACT:** In the presence of an easily prepared supported ruthenium hydroxide catalyst,  $\text{Ru}(\text{OH})_x/\text{Al}_2\text{O}_3$ , various kinds of structurally diverse primary azides including benzylic, allylic, and aliphatic ones could be converted into the corresponding nitriles in moderate to high yields (13 examples, 65–94% yields). The gram-scale (1 g) transformation of benzyl azide efficiently proceeded to give benzonitrile (0.7 g, 90% yield) without any decrease in the performance in comparison with the small-scale (0.5 mmol) transformation. The catalysis was truly heterogeneous, and the retrieved catalyst could be reused for the transformation of benzyl azide without an appreciable loss of its high performance. The present transformation of primary azides to nitriles likely proceeds via sequential reactions of imide formation, followed by dehydrogenation ( $\beta$ -elimination) to produce the corresponding nitriles. The  $\text{Ru}(\text{OH})_x/\text{Al}_2\text{O}_3$  catalyst could be further employed for synthesis of amides in water through the transformation of primary azides (benzylic and aliphatic ones) to nitriles, followed by sequent hydration of the nitriles formed. Additionally, direct one-pot synthesis from alkyl halides and  $\text{TBA}\text{N}_3$  (TBA = tetra-*n*-butylammonium) could be realized with  $\text{Ru}(\text{OH})_x/\text{Al}_2\text{O}_3$ , giving the corresponding nitriles in moderate to high yields (10 examples, 64–84% yields).



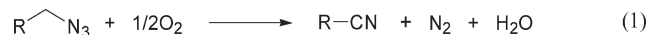
## INTRODUCTION

Nitriles have been recognized as very efficient and useful synthons for preparation of amines, amides, carbonyl compounds, and heterocycles.<sup>1</sup> Classically, nitriles have been synthesized by  $\text{S}_{\text{N}}2$  displacement of alkyl halides with inorganic cyanides (for alkyl nitriles), Sandmeyer reaction (for benzonitrile derivatives), Wittig reaction (for unsaturated nitriles), and gas-phase ammoxidation (for industrial production of acrylonitrile and benzonitrile). Although these procedures are very useful, developments of novel environmentally friendly procedures for synthesis of nitriles are highly desirable. Recently, several efficient catalytic procedures, e.g., dehydration of aldoximes or amides<sup>2</sup> and oxidative transformation of alcohols or aldehydes (or halides) with  $\text{NH}_3$  (or its surrogates such as urea and ammonium salts),<sup>3</sup> have been reported.

Azides are one of the most attractive functional groups in organic synthesis because of the dipolar character (reactivity) and can easily be introduced into organic substances by many convenient methods, e.g.,  $\text{S}_{\text{N}}2$  displacement of alkyl halides with  $\text{NaN}_3$ , even in the presence of the other functional groups.<sup>4</sup> In addition, azides are stable toward moisture and air. Although azides have been recognized as efficient and useful synthons for organic synthesis, surprisingly little is known of their authorized application as synthons at present except for Staudinger reduction, Schmidt reaction, Curtius rearrangement, decomposition to carbonyl compounds, and click reaction to triazoles.<sup>1e,4b,5</sup>

Oxidative transformation of primary azides to nitriles is an alternative attractive approach to synthesis of nitriles without elongation of the skeletal carbon chains. With regard to the transformation, several examples have been reported to date (see Table S1 in the Supporting Information).<sup>6</sup> Reported procedures require reactive stoichiometric oxidants, or catalysts with hydrogen

acceptors or strong oxidants, e.g., bromine trifluoride ( $\text{BrF}_3$ ),<sup>6a</sup> phenyliodonium diacetate,<sup>6b</sup> 2,3-dichloro-5,6-dicyanobenzoquinone,<sup>6c,d</sup> Pd metal/alkynes,<sup>6e</sup> and  $\text{CuI}/\text{tert}$ -butyl hydroperoxide.<sup>6f</sup> As far as we know, catalytic oxidative transformation of primary azides to nitriles with  $\text{O}_2$  (or air) as a sole oxidant has never been reported so far. If heterogeneously catalyzed transformation with  $\text{O}_2$  (or air) could be realized, it would become one of the greenest procedures because (i) only  $\text{N}_2$  and  $\text{H}_2\text{O}$  are formed as byproducts [eq 1], (ii) use of toxic metal cyanide reagents can be avoided, and (iii) catalyst/product(s) separation and reuse of catalyst are very easy.



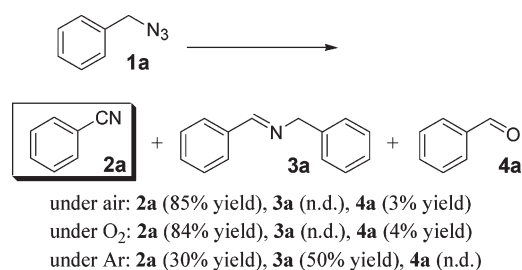
Recently, we have developed efficient heterogeneous catalysts for functional group transformations including oxidative dehydrogenation, oxygenation, hydrogen transfer reactions, and hydration.<sup>7</sup> Our strategy to design efficient heterogeneous catalysts is creation of highly (monomerically) dispersed metal hydroxide species on appropriate supports (especially ruthenium hydroxide species).<sup>7</sup> Herein, we report that novel transformation of aerobic oxidative synthesis of nitriles from primary azides (or alkyl halides and  $\text{TBA}\text{N}_3$  (TBA = tetra-*n*-butylammonium)) could be realized with an easily prepared supported ruthenium hydroxide catalyst,  $\text{Ru}(\text{OH})_x/\text{Al}_2\text{O}_3$ .

## RESULTS AND DISCUSSION

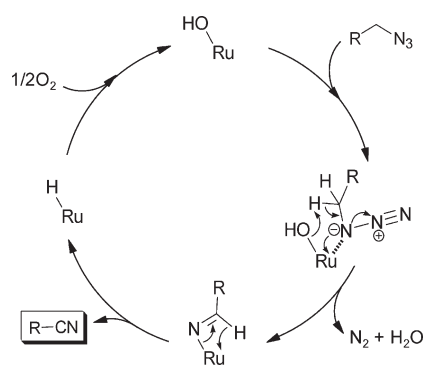
Initially, transformations of benzyl azide (**1a**) to benzonitrile (**2a**) were carried out with various catalysts under different conditions (Scheme 1 and Table S2). When the transformation

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**Scheme 1. Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-Catalyzed Transformation of 1a to 2a<sup>a</sup>**


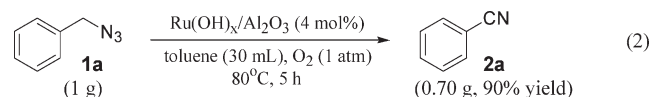
<sup>a</sup> Reaction conditions: **1a** (0.5 mmol), catalyst (metal, 4 mol %), solvent (2 mL), 80 °C, 5 h. Yields are based on **1a** and were determined by GC.

**Scheme 2. Possible Reaction Mechanism for the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-Catalyzed Transformation of Primary Azides to Nitriles**


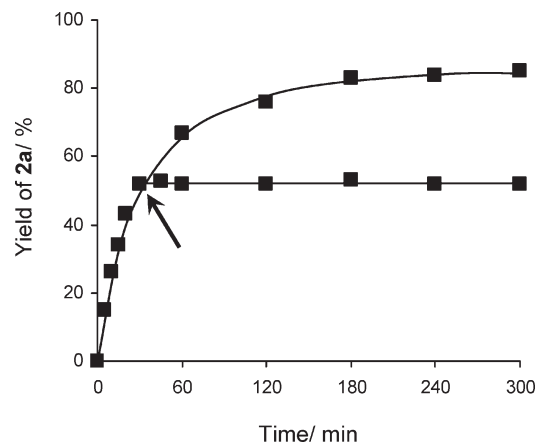
of **1a** was carried out with Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (4 mol % with respect to **1a**) in toluene at 80 °C under an air atmosphere, 85% yield of **2a** was obtained for 5 h.<sup>8</sup> In this case, a small amount of benzaldehyde (**4a**) was formed as a byproduct (3%). It was confirmed by mass analysis of the gas phase that H<sub>2</sub> gas was not formed and N<sub>2</sub> gas was formed during transformation of **1a** to **2a**. Reaction rates were almost independent of partial pressures of O<sub>2</sub> (0.2–1 atm).

The ruthenium hydroxide (Ru-OH) species possess both Lewis acid and Brønsted base sites on the same metal sites.<sup>7</sup> Therefore, the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-catalyzed transformation of primary azides to nitriles possibly proceeds via the concerted activation of primary azides by the Lewis acid and Brønsted base sites to form imide intermediates. Then, β-elimination takes place to produce the corresponding nitriles with formation of the hydride (Ru-H) species.<sup>7b</sup> The Ru-OH species is easily regenerated by reaction of the Ru-H species with O<sub>2</sub> (even air),<sup>9</sup> and the catalytic cycle would be completed (Scheme 2).

In order to show practical usefulness of the present procedure in organic synthesis, the gram-scale transformation of **1a** (1 g, 15-fold scale-up) was carried out. The transformation efficiently proceeded to give 0.70 g of **2a** (90% yield) without any decrease in the performance in comparison with the small-scale transformation in Scheme 1 [eq 2].



When the transformation of **1a** was carried out under Ar atmosphere, a significant amount of *N*-benzylidenebenzylamine



**Figure 1.** Verification of heterogeneous catalysis for transformation of **1a** to **2a**. The reaction was carried out under the conditions described in Scheme 1. The arrow indicates the removal of Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> by hot filtration.

(**3a**, 50%) was formed as a byproduct. Under Ar atmosphere, there are several paths for the regeneration of the Ru-OH species: (i) hydrolytic decomposition of the imide intermediate, (ii) hydrogenation of an imine, and (iii) hydrogenation of a nitrile (Scheme S1). Therefore, the amount of a nitrile can exceed that of the ruthenium catalyst used. However, under Ar atmosphere, the selectivity to the desired nitrile was low because of side reactions (ii) and (iii). In contrast, under aerobic conditions, the reaction of the Ru-H species with O<sub>2</sub> easily takes place.<sup>9</sup> Thus, the corresponding alkylamines were hardly detected and the selectivity to the desired nitrile was high under aerobic conditions (Scheme 1).

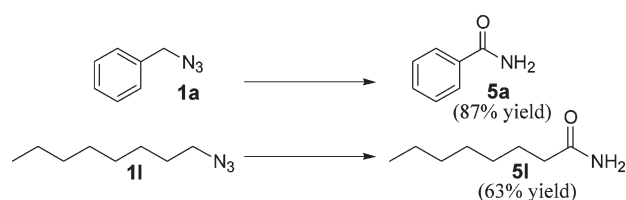
Various kinds of supported metal hydroxide catalysts and ruthenium-based catalysts were applied to the transformation of **1a** to **2a** (Table S2). Under the present conditions, no reaction proceeded in the absence of the catalyst or in the presence of just Al<sub>2</sub>O<sub>3</sub> or the catalyst precursor RuCl<sub>3</sub>·*n*H<sub>2</sub>O. Among various supported metal hydroxide catalysts examined (for example, Ru, Au, Ag, Cu, Pd, Rh, and Ir), only Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> showed the high catalytic performance. Commonly utilized ruthenium complexes such as Ru(acac)<sub>3</sub> (acac = acetylacetonato), RuCl<sub>2</sub>(PPh<sub>3</sub>)<sub>3</sub>, Ru<sub>3</sub>(CO)<sub>12</sub>, and RuCl<sub>2</sub>(bpy)<sub>3</sub>·6H<sub>2</sub>O (bpy = 2,2'-bipyridyl) were not effective. Other ruthenium-based heterogeneous catalysts such as Ru/C (Ru metal supported on activated carbon), Ru-hydroxyapatite (Ru<sup>3+</sup>-exchanged hydroxyapatite),<sup>10</sup> and RuO<sub>2</sub> anhydrous (bulk oxide) did not show high catalytic performance. The catalytic activity of Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> was much higher than those of Ru(OH)<sub>x</sub> (unsupported bulk hydroxide) and a simple physical mixture of Ru(OH)<sub>x</sub> and Al<sub>2</sub>O<sub>3</sub>. Therefore, the highly dispersed ruthenium hydroxide species would play an important role for the present transformation.

To verify whether the observed catalysis is derived from solid Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> or leached ruthenium species, the transformation of **1a** to **2a** was carried out under the conditions described in Scheme 1, and Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> was removed from the reaction mixture by hot filtration at ca. 50% conversion of **1a**. Then, the reaction was again carried out with the filtrate under the same conditions. In this case, no further production of **2a** was observed (Figure 1). In addition, it was confirmed by inductively coupled plasma atomic emission spectroscopy analysis that no ruthenium was detected in the filtrate (below 0.03%). All of these experimental

**Scheme 3. Scope of the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-Catalyzed Transformation of Primary Azides to Nitriles<sup>b</sup>**

**1a** (R=Ph): 85% yield (5 h), **1b** (R = 4-MeOC<sub>6</sub>H<sub>4</sub>): 90% yield (3 h),  
**1c** (R = 3-MeOC<sub>6</sub>H<sub>4</sub>): 86% yield (5 h), **1d** (R = 4-MeC<sub>6</sub>H<sub>4</sub>): 88% yield (2.5 h),  
**1e** (R = 4-ClC<sub>6</sub>H<sub>4</sub>): 89% yield (5 h), **1f** (R = 4-PhC<sub>6</sub>H<sub>4</sub>): 92% yield (6 h),  
**1g** (R = 4-CF<sub>3</sub>C<sub>6</sub>H<sub>4</sub>): 82% yield (12 h), **1h** (R = 4-NO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>): 65% yield (24 h)<sup>a</sup>,  
**1i** (R = 2-naphthyl): 90% yield (5 h), **1j** (R = 3-pyridyl): 66% yield (24 h),  
**1k** (R = C<sub>6</sub>H<sub>5</sub>CH=CH): 71% yield (24 h)<sup>a</sup>, **1l** (R = *n*-C<sub>7</sub>H<sub>15</sub>): 75% yield (24 h),  
**1m** (R = cyclohexyl): 94% yield (10 h)

<sup>a</sup> Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (8 mol %). <sup>b</sup> Reaction conditions: substrate (0.5 mmol), Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (4 mol %), toluene (2 mL), air (1 atm), 80 °C. Yields are based on azides and were determined by GC.

**Scheme 4. Scope of the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-Catalyzed Transformation of Primary Azides to Amides<sup>a</sup>**

<sup>a</sup> Reaction conditions: substrate (0.5 mmol), Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (5 mol %), water (3 mL), air (3 atm), 130 °C, 24 h. Yields are based on azides and were determined by GC.

results can rule out any contribution to the observed catalysis from ruthenium species that leached into the reaction solution, and the observed catalysis is intrinsically heterogeneous.<sup>11</sup>

Next, scope of the present Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-catalyzed system with regard to various kinds of structurally diverse primary azides was examined (Scheme 3). Transformations of benzylic azides **1a–1i**, which contain electron-donating as well as electron-withdrawing substituents, efficiently proceeded to afford the corresponding aromatic nitriles in moderate to high yields. Reaction rates for benzylic azides with electron-donating substituents were larger than those with electron-withdrawing ones, suggesting the electrophilic nature of the present Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-catalyzed transformation. Reactive functional groups such as chloro and nitro groups intrinsically remained intact; no dechlorination and reduction of the nitro group proceeded. Also, 3-(azidemethyl)pyridine **1j** was converted into the corresponding nitrile. In the transformation of an allylic azide **1k**, the corresponding unsaturated nitrile could be obtained without isomerization, hydrogenation, and hydration of the double bond. Aliphatic nitriles could efficiently be synthesized in the present system using azides as substrates. After the reaction was completed, Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> could easily be retrieved from the reaction mixture by simple filtration. The retrieved catalyst could be reused for the transformation of **1a** to **2a** without an appreciable loss of the catalytic performance; **2a** was obtained in 80% and 81% yields for the first and the second reuse experiments, respectively, under the conditions described in Scheme 3.

When the transformation of primary azides was carried out in water, the corresponding primary amides were obtained as major products. For example, transformations of **1a** (benzylic azide) and **1l** (aliphatic azide) gave benzamide (**5a**) and *n*-octanamide

**Scheme 5. Scope of the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>-Catalyzed One-Pot Synthesis of Nitriles<sup>b</sup>**

**6a** (R=Ph, X=Cl): 83% yield (10 h), **6b** (R = 4-MeOC<sub>6</sub>H<sub>4</sub>, X=Cl): 83% yield (6 h),  
**6c** (R = 3-MeOC<sub>6</sub>H<sub>4</sub>, X=Cl): 81% yield (8 h), **6d** (R = 4-MeC<sub>6</sub>H<sub>4</sub>, X=Cl): 84% yield (8 h),  
**6e** (R = 4-ClC<sub>6</sub>H<sub>4</sub>, X=Cl): 78% yield (10 h), **6f** (R = 4-PhC<sub>6</sub>H<sub>4</sub>, X=Br): 80% yield (10 h),  
**6i** (R = 2-naphthyl, X=Br): 72% yield (5 h), **6k** (R = C<sub>6</sub>H<sub>5</sub>CH=CH): 76% yield (24 h),  
**6l** (R = *n*-C<sub>7</sub>H<sub>15</sub>, X=I): 76% yield (24 h)<sup>a</sup>, **6m** (R = cyclohexyl, X=Br): 64% yield (24 h)<sup>a</sup>

<sup>a</sup> Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (8 mol %). <sup>b</sup> Reaction conditions: substrate (0.5 mmol), TBAN<sub>3</sub> (0.55 mmol), Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (6 mol %), acetonitrile (2 mL), air (1 atm), 80 °C. Yields are based on alkyl halides and were determined by GC.

(**5l**) in 87% and 63% yields, respectively (with the formation of aldehydes as main byproducts (~10%)) (Scheme 4).<sup>12</sup> The reaction profiles for the transformation of **1a** in water showed that **2a** was initially formed, followed by the formation of **5a**. In addition, it was confirmed in a separate experiment that the hydration of **2a** to **5a** efficiently proceeded in the presence of Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> under the similar conditions.<sup>7d,13</sup> Therefore, the transformation of primary azides to primary amides in water proceeds by sequential reactions, namely, the oxidative transformation of primary azides to nitriles, followed by the hydration to afford the corresponding primary amides.

Additionally, direct one-pot synthesis of nitriles from alkyl halides and TBAN<sub>3</sub> could be realized with Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (Scheme 5). The present one-pot procedure can completely avoid isolation of primary azides (explosive in some cases), which is very important advantage in comparison with the step-by-step synthesis.

## CONCLUSION

In summary, novel transformation of aerobic oxidative synthesis of nitriles from primary azides (or alkyl halides and TBAN<sub>3</sub>) could be realized for the first time with Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>. The catalysis was truly heterogeneous, and the retrieved catalyst could be reused. The results demonstrated herein will become a good candidate for green nitrile synthesis, which can completely avoid use of harsh reaction conditions and conventional hazardous stoichiometric reagents such as inorganic cyanides.

## EXPERIMENTAL SECTION

**General.** GC analyses were performed with a FID detector equipped with a capillary column. Mass spectra were recorded at an ionization voltage of 70 eV. <sup>1</sup>H and <sup>13</sup>C NMR spectra were measured at 270 and 67.8 MHz, respectively, with TMS as an internal standard. Alkyl halides, benzyl azide (**1a**), nitriles, amides, and solvents were commercially available and purified prior to the use.<sup>14</sup> Ru hydroxyapatite (Ru 9.1 wt %) and Ru/C (5.0 wt %) were also commercially available. Organic azides (**1b**,<sup>15a</sup> **1c**,<sup>15b</sup> **1d**,<sup>15c,d</sup> **1e**,<sup>15e</sup> **1f**,<sup>15f</sup> **1g**,<sup>15g</sup> **1h**,<sup>15e</sup> **1i**,<sup>15f</sup> **1j**,<sup>15h</sup> **1k**,<sup>15i</sup> **1l**,<sup>15c,d</sup> and **1m**<sup>15i</sup>) were prepared by the nucleophilic substitution of the corresponding alkyl halides with NaN<sub>3</sub>.

**Preparation of Catalysts.** Supported ruthenium hydroxide catalyst, Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>, was prepared as follows.<sup>7</sup> Al<sub>2</sub>O<sub>3</sub> powder (2.0 g) pretreated at 550 °C for 3 h was vigorously stirred with 60 mL of an aqueous solution of RuCl<sub>3</sub> (8.3 mM) at room temperature (ca. 20 °C). After 15 min, the pH of the solution was adjusted to 13.2 by addition of aqueous solution of NaOH (1 M), and the resulting slurry was stirred for 24 h. The solid was then filtered off, washed with a large amount of

deionized H<sub>2</sub>O, and dried in vacuo to afford Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub>. The contents of ruthenium were 2.1–2.2 wt %. Other metal hydroxide catalysts were prepared in the similar way.<sup>7</sup>

**Transformation of 1a to 2a.** Into a Pyrex-glass screw cap vial were successively placed Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (96 mg, Ru 4 mol %), **1a** (66.6 mg, 0.5 mmol), and toluene (2 mL) (Figure S1). A Teflon-coated magnetic stir bar was added, and the reaction mixture was vigorously stirred (800 rpm) at 80 °C for 5 h in 1 atm of air. After the reaction was completed, the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> catalyst was removed by filtration. Then, the filtrate was analyzed by GC and GC–MS (conversion of **1a**, 99%; yield of **2a**, 85%; yield of **4a**, 3%). The product (**2a**) was isolated by silica gel column chromatography (initial, *n*-hexane; after toluene was eluted, ethyl acetate) (42.8 mg, 83% isolated yield).

**Gram-Scale Transformation of 1a to 2a.** Into a Pyrex-glass screw cap vial were successively placed Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (1.4 g, Ru 4 mol %), **1a** (1.0 g, 7.5 mmol), and toluene (30 mL). A Teflon-coated magnetic stir bar was added, and the reaction mixture was vigorously stirred (800 rpm) at 80 °C for 5 h in 1 atm of air. After the reaction was completed, the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> catalyst was removed by filtration. Then, the filtrate was analyzed by GC and GC–MS (conversion of **1a**, >99%; yield of **2a**, 92%; yield of **4a**, 2%). The product (**2a**) was isolated by silica gel column chromatography (initial, *n*-hexane; after toluene was eluted, ethyl acetate) (0.70 g, 90% isolated yield).

**Transformation of 1a to 5a.** **1a** (66.6 mg, 0.5 mmol), Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (120 mg, Ru 5 mol %), and water (3 mL) were placed in a Teflon vessel with a magnetic stir bar. The Teflon vessel was attached inside an autoclave, and the reaction mixture was vigorously stirred (800 rpm) at 130 °C (bath temperature) for 24 h in 3 atm of air. After the reaction was completed, the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> catalyst was removed by filtration. The filtrate was diluted with ethanol (10 mL) and then analyzed by GC and GC–MS (conversion of **1a**, >99%; yield of **5a**, 87%; yield of **2a**, 1%; yield of **4a**, 9%).

**Transformation of 6a to 2a.** Into a Pyrex-glass screw cap vial were successively placed Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (144 mg, Ru 6 mol %), **6a** (63.0 mg, 0.5 mmol), TBAN<sub>3</sub> (156 mg, 0.55 mmol), and toluene (2 mL). A Teflon-coated magnetic stir bar was added, and the reaction mixture was vigorously stirred (800 rpm) at 80 °C for 10 h in 1 atm of air. After the reaction was completed, the Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> catalyst and the TBA halide formed were removed by filtration. Then, the filtrate was analyzed by GC and GC–MS (conversion of **6a**, >99%; yield of **2a**, 83%; yield of **1a**, 8%; yield of **4a**, 4%).

**Catalyst Reuse.** After the reaction was completed, the spent Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> catalyst was retrieved by filtration, washed with acetone, aqueous solution of NaOH (0.01 M), and deionized H<sub>2</sub>O, and then dried in vacuo prior to being recycled.

## ■ ASSOCIATED CONTENT

Supporting Information. Full experimental details, Tables S1 and S2, Figure S1, and Scheme S1. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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intermediate (Scheme S1). The formation of **4a** could be suppressed by increasing the pressure of air. For example, **5a** was obtained in 87% yield with the formation of **4a** (9%) in 3 atm of air (Scheme 4).

(13) In the presence of Ru(OH)<sub>x</sub>/Al<sub>2</sub>O<sub>3</sub> (4 mol%), the hydration of **2a** (1 mmol) in water (3 mL) at 140 °C (bath temperature) efficiently proceeded to afford **5a** in 99% yield for 6 h.

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