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Ferrocene Redox Controlled Reversible Immobilization of Ruthenium Carbene in Ionic Liquid: A Versatile Catalyst for Ring-Closing Metathesis

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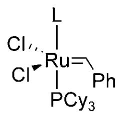
Abstract: A ferrocene-tagged ruthenium carbene **15** that can be reversibly immobilized in an ionic liquid (IL) *via* the controlled oxidation and reduction of a ferrocene tag was prepared. This offers a new strategy which uses redox chemistry to control immobilization and to recycle both the catalyst and the IL. In this experiment, 11 recycles were performed for the ring-closing metathesis (RCM) of a substrate using **16** as the catalyst in an ionic liquid (IL). More importantly, after the reaction was completed, the ruthenium catalyst was easily separated from the supporting IL by just adding decamethylferrocene (DMFc) to reduce the cationic ferrocene and then extracting it with benzene. Thus, this recycle system offers an easy way to recycle both the ruthenium catalyst and the IL.

Keywords: ferrocene ligands; homogeneous catalysis; ring-closing metathesis; ruthenium

Introduction

Since the discovery of well-defined modern ruthenium catalysts **1**–**4**, and **5**–**11**,[1] olefin metathesis has become one of the most important tools for carbon-carbon bond formation.[2] However, like many other homogeneous catalysts, these ruthenium carbene complexes are difficult to recycle and are usually destroyed after a single use. Another serious problem is the removal of Ru residuals from the products. To



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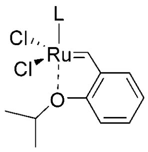

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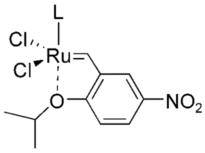

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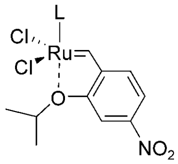

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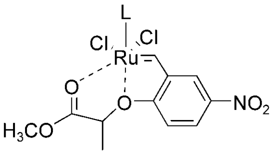

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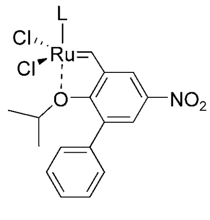

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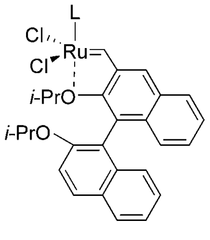

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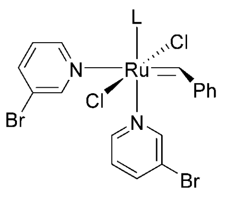

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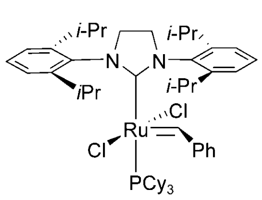


11

1, 3 L = PCy_3 ;

2, 4, 5, 6, 7, 8, 9, 10 L =

overcome these disadvantages of ruthenium carbene catalysts, various strategies have been employed to recycle and to reuse them.[3]

Traditionally, Ru carbene complexes can be recycled and reused *via* immobilization on a solid or polymer surface through covalent or non-covalent bonds.[4] More recently, utilization of a tag has been extensively employed for the immobilization of transition metal catalysts.[5] For example, a catalyst may become suitable for use in ionic liquid (IL) by introducing a cation- or anion-appended ligand to the ruthenium metal center.[6] Another method that has been adapted for recycle and reuse is to introduce a fluorous tag to Hoveyda's boomerang ligand which makes the catalyst suitable for use in fluorous solvents.[7] The key factors in this tagging strategy are the polarity and solubility of the catalyst which are largely determined by the connecting tag. If an Ru catalyst is connected to a redox switchable phase tag, dramatic polarity changes occur in the catalyst when the tag is switched. The catalyst will then shift from one solvent phase to another that has a different polarity, thus offering a better chance to separate and recycle both the catalyst and the supporting material. A previous report demonstrated that a redox-switchable phase-tagged Ru carbene catalyst could be recycled in a single solvent, presenting a new way to employ switchable phase tags for the recycling of homogeneous catalysts.[8] This current study shows that the recyclability of an Ru catalyst with a redox-switchable phase tag can be significantly enhanced in a biphasic solvent system containing an ionic liquid and a non-polar solvent.

Results and Discussion

Scheme 1 illustrates the reaction of (*E*)-[4-isopropoxy-3-(prop-1-enyl)phenyl]methanol **12** with 4-ferrocenylbutanoic acid **13** to give the ferrocene-tagged ligand **14** in good yield. The treatment of **14** with **2** in the presence of CuCl in CH_2Cl_2 at 40 °C, as described by Hoveyda and co-workers[4m] resulted in the exchange of the styrene group to give the ferrocene-tagged ruthenium complex **15** in good yield (68%) as a greenish crystalline solid.

Complex **15** was subjected to cyclic voltammetry (CV) in order to select a suitable oxidant. The well behaved CV peaks of the ferrocene tag indicate that the reaction is reversible and the redox potential is +0.534 V (see Figure 1). Redox peaks for the Ru(II) center are also observed at higher potentials. The $E_{1/2}$ for this reaction is +1.016 V. The separation between

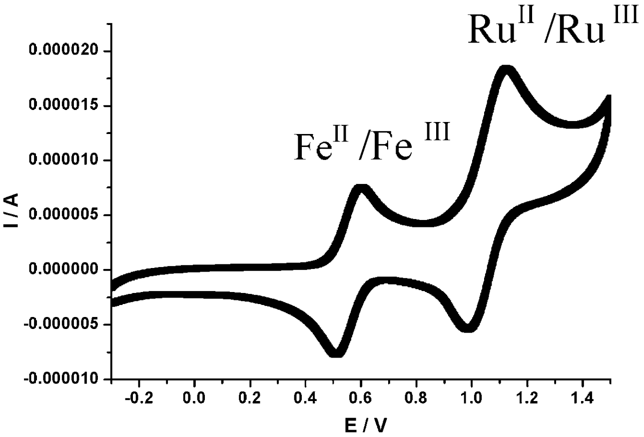
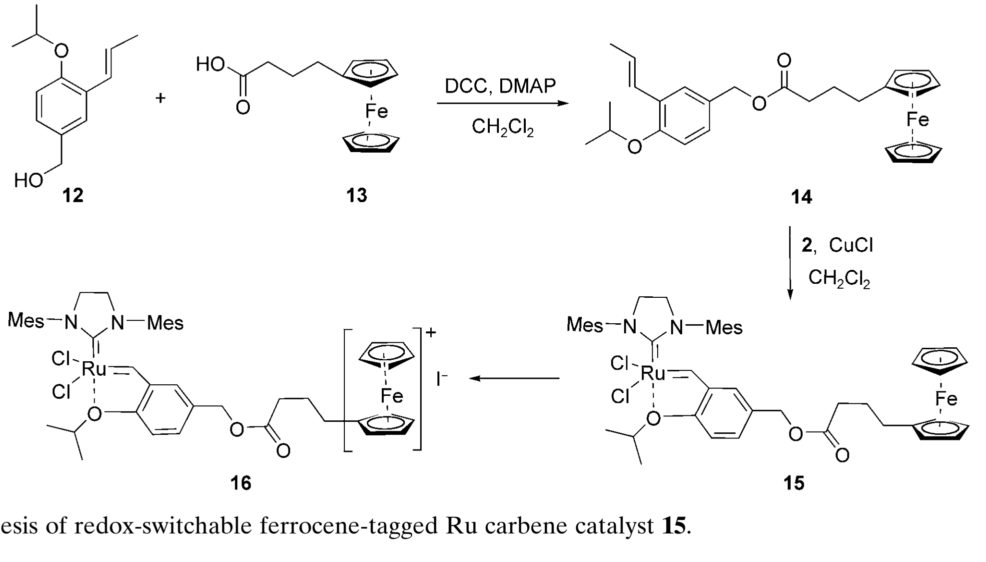


Figure 1. Cyclic voltammogram of the ferrocene-tagged **15**. $E_{1/2}$ (Fe^{II}/Fe^{III}) = +0.534 V (ΔE_p = 90 mV), $E_{1/2}$ (Ru^{II}/Ru^{III}) = +1.016 V (ΔE_p = 136 mV) *versus* SCE.



Scheme 1. Synthesis of redox-switchable ferrocene-tagged Ru carbene catalyst **15**.

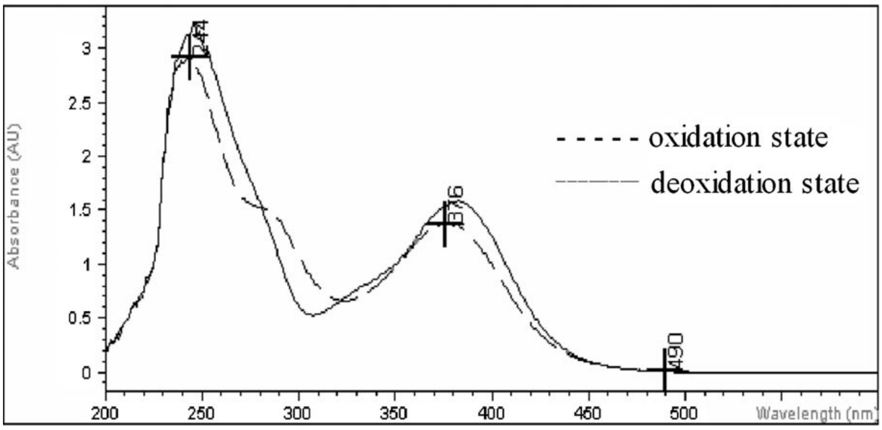


Figure 2. The UV/Vis spectra of ruthenium carbene complexes of **15** and **16**.

the ferrocence and the Ru redox events is more than sufficient for selective oxidation of the ferrocene.

Several oxidants with redox potentials between +0.699 V and +0.806 V, including $AgBF_4$ ($E_{1/2}$= +0.75 V), $AgPF_6$ ($E_{1/2}$=+0.75 V), benzoquinone ($E_{1/2}$=+0.699 V), and I_2 (+0.806 V in CH_2Cl_2) were tested as oxidizers for the ferrocene tag in CH_2Cl_2. The reaction of **15** with $AgBF_4$, or $AgPF_6$ resulted in a very unstable yellow complex which showed no activity in ring-closing metathesis (RCM) reactions. The ferrocene tag could be oxidized by benzoquinone in the presence of an HPF_6-water solution, resulting in an air-sensitive green complex. This complex was very active for RCM reactions under inert gas, but it decomposed immediately in the presence of air. When I_2 was employed as an oxidant, the reaction proceeded smoothly to give cationic ferrocene-tagged ruthenium complexes, identified as **16**, in nearly quantitative yield (>98%). The oxidation of **15** *in situ* with I_2 was confirmed by ^{1}H NMR and ESI-MS. In the ^{1}H NMR spectra the benzylidene proton shifted from 16.523 ppm to 15.494 ppm. The MS of catalyst **15** has a dominant peak at m/z=910.2 $[M]^+$ (calcd.: 910.19). The spectrum of catalyst **16** has a peak at m/z= 1059.6 $[M+Na]^+$ (calcd.: 1060.08) and a fragment peak at m/z=911.4. This difference corresponds to the loss of one I^- unit. In order to verify that iodide does not exchange with the Ru−Cl to give Ru−I, another ESI-MS for catalyst **16** was obtained under different conditions. A dominant peak for $[C_{46}H_{54}Cl_2N_2O_3RuFe]^+$ appears at m/z=910.12 (calcd.: 910.19) in the +c ESI full MS. A dominant peak for I^- is also found at m/z=127.16 (calcd.: 126.90) in the −c ESI full MS. This indicates that Cl is not displaced by I and the anion is I^-.

Further evidence that **15** has been oxidized to **16** is seen in their UV/Vis spectra (Figure 2). The UV/Vis spectra of the oxidation product **16** showed a new peak at 290 nm. Further study shows that the ferrocene-tagged ruthenium carbene **15** and the cationic ferrocene-tagged **16** are air- and heat-stable complexes which are comparable to their parent compound **4**.

As expected, **15** and **16** have very different solubilities due to the different properties of the ferrocene tag. Compound **15** exhibits very good solubility in non-polar solvents, such as benzene, toluene, and hexanes. On the other hand, **16** is very soluble in polar solvents, such as alcohols, acetone, and acetyl acetate. More importantly, the solubility of these complexes can be adjusted by varying the ferrocene tag through redox reactions. An experiment to demonstrate this concept was conducted in a biphasic system containing benzene and an IL (see Figure 3).

With its neutral ferrocene tag, **15** showed very good solubility in the benzene solvent (upper layer), whereas only a trace amount of **15** was found in the IL (lower layer). When I_2 was added, the ferrocene tag was immediately oxidized to the cationic ferrocene to give **16** which was very soluble in the IL. A further study showed that the cationic ferrocene could be reduced to neutral ferrocene by adding one equivalent decamethylferrocene (DMFc) ($E_{1/2}$=−0.59 V) to give **15** which then shifted back to the benzene layer. This procedure was completely reversible, and at least 4 cycles were repeated. Figure 3 shows the result.

Diethyl diallymalonate **17** was chosen as a test diene to investigate the catalytic activity of **15** and **16** for RCM. The relative conversion rates for RCM by **15** and **16** under similar conditions are shown in Figure 4. At 30 °C, the catalytic activities of **15** and **16** are slightly lower than that of the parent compound **4**. This can be explained by the alkyl substitution at the *para*-position which enhances the electron donor behaviour of the isopropoxy group to the Ru center. The ferrocene-tagged **15** exhibits a slightly better performance than the cationic ferrocene-tagged **16**.

Nevertheless, both **15** and **16** are active RCM catalysts. For both catalysts, high conversions (> 94%) were achieved after 30 min for the RCM of **17** at

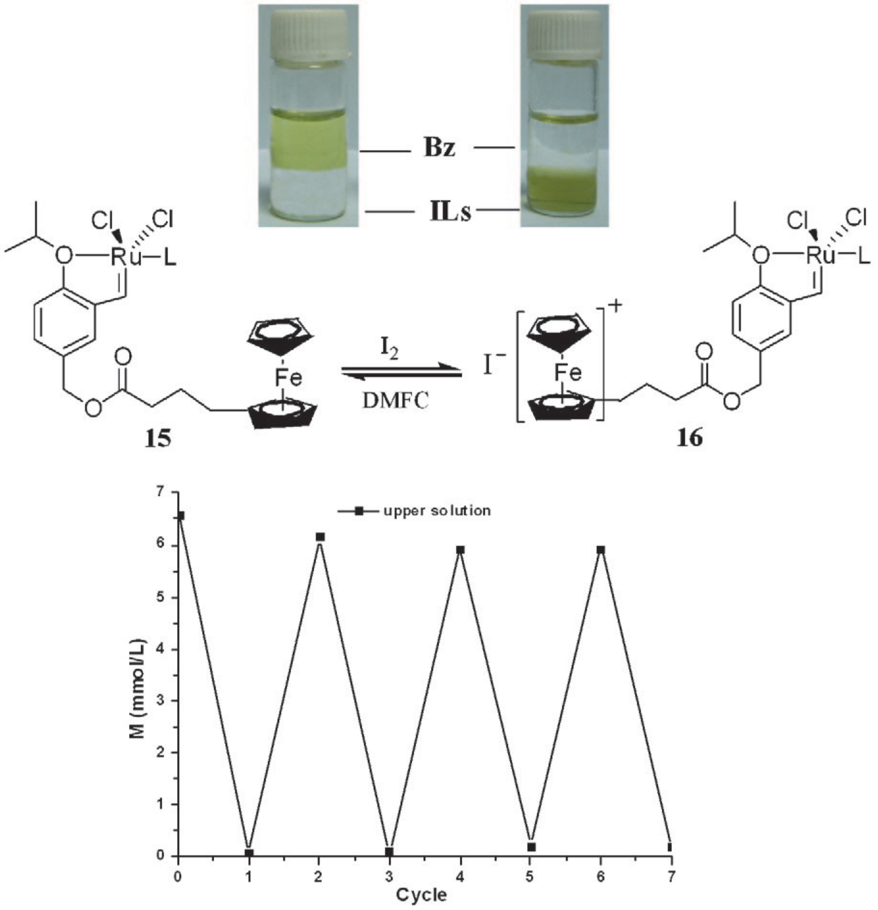


Figure 3. Redox controlled ferrocene-tagged **15** and **16** exhibiting different solubility in ionic liquid (ILs) and benzene (Bz). (Switching on and off of the ferrocene tag detected by UV/Vis at $\lambda = 381$ nm.)

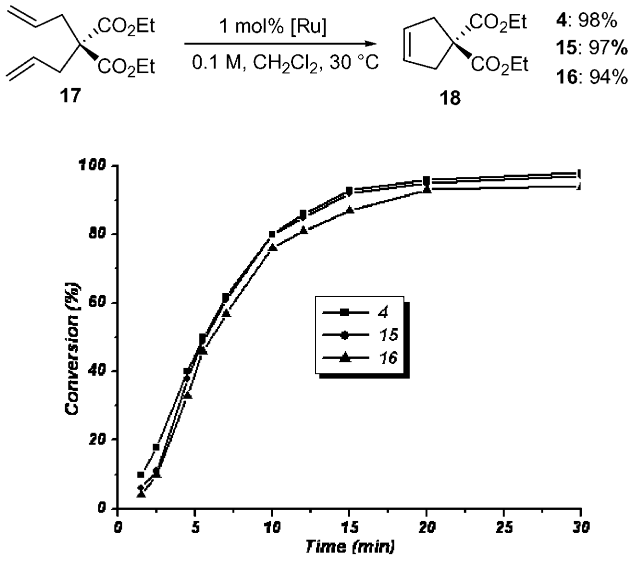


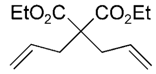
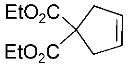
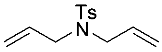
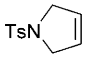
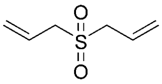
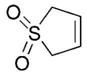
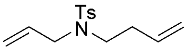
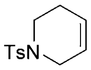
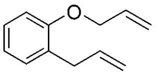
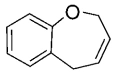
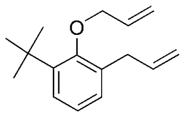
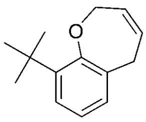
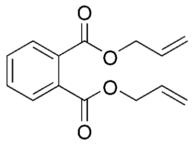
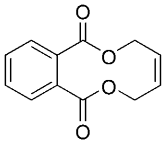
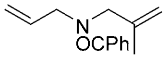
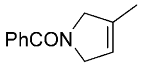
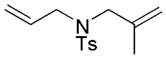
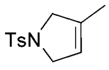
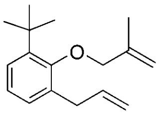
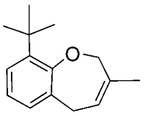
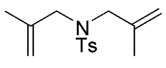
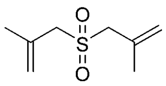
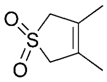
Figure 4. Relative conversion rates of **15** and **16** using 1 mol% catalyst in CH_2Cl_2 at 30 °C.

30 °C, which is comparable with **4** under similar reaction conditions.[9] Compared with other reported Ru carbene catalysts[1a–h], both **15** and **16** are moderately active RCM catalysts.

Further studies showed that **15** and **16** are also active for ring closures of the N-protected substrates **19**, **23**, **31**, **33** and a sulfur-containing substrate **21**. These reactions resulted in the formation of either five-, or six-membered rings with di- or trisubstituted double bonds. The products were obtained in high conversions with low catalyst loading (0.1–1.0 mol%) (see Table 1).

For the bulky-substituted dienes **37** and **39**, both **15** and **16** gave low conversions at room temperature in CH_2Cl_2. However RCM was achieved in good conversions for both catalysts at elevated temperatures (45 °C in CH_2Cl_2 or 80 °C in toluene) with a longer reaction time (24 h). The conversion of oxygen-containing dienes, **25**, **27**, and **35** was consistently lower for **16** than for **15**. These substrates form seven-membered rings with a di- or trisubstituted double bond. Nevertheless, both **15** and **16** are highly active catalysts for a large scope of RCM reactions, and are tol-

Table 1. Application of catalysts **15** and **16** to different substrates.[a]

Entry	Substrate	Product	Cat.(mol %)	Conditions	Conv. (Yield)
1	 **17**	 **18**	**15** (0.1)	4.0 h, 35 °C	> 98% (98%)
			16 (0.1)	4.0 h, 35 °C	> 98% (98%)
2	 **19**	 **20**	**15** (0.2)	0.5 h, 35 °C	> 98% (97%)
			16 (0.2)	0.5 h, 35 °C	98% (98%)
3	 **21**	 **22**	**15** (0.2)	0.5 h, 35 °C	98% (97%)
			16 (0.2)	0.5 h, 35 °C	98% (97%)
4	 **23**	 **24**	**15** (0.2)	0.5 h, 35 °C	98% (98%)
			16 (0.2)	0.5 h, 35 °C	98% (98%)
5	 **25**	 **26**	**15** (0.2)	0.5 h, 35 °C	> 98% (91%)
			16 (0.2)	0.5 h, 35 °C	90% (87%)
6	 **27**	 **28**	**15** (0.2)	0.5 h, 35 °C	98% (98%)
			16 (0.2)	0.5 h, 35 °C	92% (85%)
7	 **29**	 **30**	**15** (1.0)	8.0 h, 35 °C	98% (97%)
			16 (1.0)	8.0 h, 35 °C	98% (96%)
8	 **31**	 **32**	**15** (1.0)	0.5 h, 35 °C	> 98% (97%)
			16 (1.0)	0.5 h, 35 °C	> 99% (97%)
9	 **33**	 **34**	**15** (1.0)	0.5 h, 35 °C	> 98% (93%)
			16 (1.0)	0.5 h, 35 °C	> 98% (96%)
10	 **35**	 **36**	**15** (1.0)	12 h, 35 °C	> 84% (74%)
			16 (1.0)	12 h, 35 °C	> 83% (73%)
11	 **37**	 **38**	**15** (2.5)	24 h, 80°C[b]	95% (93%)
			16 (2.5)	24 h, 80°C[b]	85% (84%)
12	 **39**	 **40**	**15** (2.5)	24 h, 45 °C	98% (98%)
			16 (2.5)	24 h, 45 °C	98% (98%)

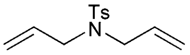
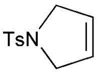
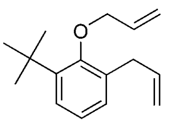
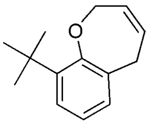
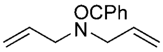
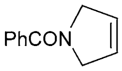
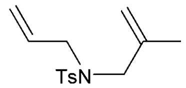
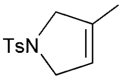
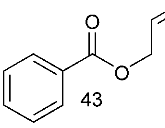
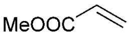
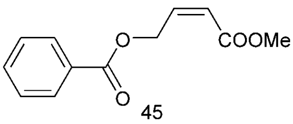
[a] Reactions were conducted in CH_2Cl_2 and relative conversion rates of substrates were obtained by ^1H NMR spectroscopy.

[b] Reaction in toluene.

erant to many functional groups which is similar to the behaviour of their parent compound **4**.

To test the recyclability, the ferrocene-tagged catalyst **16** was evaluated for RCM in 1-butyl-3-methylimidazolium hexafluorophosphate (BMIPF$_6$) ionic liquid (IL). Table 2 shows that with different amounts of catalyst loading (0.1–2.5 mol%), the cationic ferrocene-tagged catalyst **16** can be recycled and reused 2

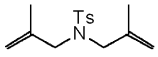
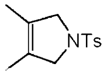
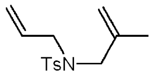
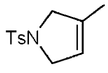
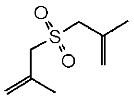
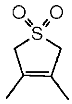
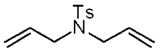
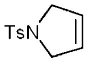
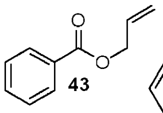
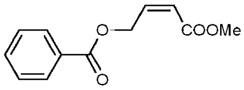
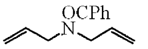
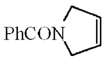
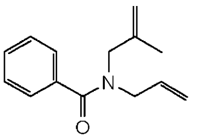
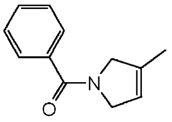
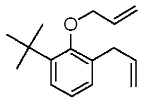
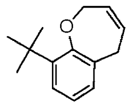
Table 2. Recycling and reuse of **16** in BMI·PF$_6$.

Substrate	Product	Cat. (mol%)	Cycle	Conv. [%][a] (Time)
 19	 20	2.5	1	>98 (0.5 h)
			2	>98 (0.5 h)
			3	>98 (0.5 h)
			4	>98 (0.5 h)
			5	>98 (0.5 h)
			6	>98 (1.0 h)
			7	>98 (1.0 h)
			8	>98 (2.5 h)
			9	>98 (12 h)
			10	>98 (12 h)
			11	73 (24 h)
		1	1	>98 (0.5 h)
			2	>98 (0.5 h)
			3	>98 (0.5 h)
			4	>98 (0.5 h)
			5	>98 (1.0 h)
			6	>98 (12 h)
			7	>55 (12 h)
		0.5	1	>98 (0.5 h)
			2	>98 (0.5 h)
			3	>98 (12 h)
			4	>50 (12 h)
		0.1	1	>98 (1.0 h)
			2	>98 (12 h)
			3	>40 (0.5 h)
 27	 28	2.5	1	>98 (40min)
			2	>98 (40min)
			3	>98 (40min)
			4	>98 (1.0 h)
			5	>98 (1.0 h)
			6	>98 (2.5 h)
			7	81 (12 h)
		0.5	1	>98 (40 min)
			2	>98 (2.0 h)
			3	>98 (12 h)
			4	>30 (12 h)
 41	 42	2.5	1	>98 (0.5 h)
			2	>98 (0.5 h)
			3	>98 (0.5h)
			4	>98 (40min)
			5	>98 (12h)
			6	42 (24 h)
		0.5	1	>98 (0.5 h)
			2	>98 (1.0 h)
			3	>40 (12 h)
 33	 34	2.5	1	>98(1.0 h)
			2	>98 (1.0 h)
			3	>98 (1.5 h)
			4	>98 (3.0 h)
			5	>92 (12 h)
			6	90 (24 h)
		1	1	>98 (1.0 h)
			2	>98 (1.0 h)
			3	>98 (3.0 h)
			4	>98 (12 h)
			5	>70 (12 h)
 43  44	 45	2.5	1	>98 (12 h)
			2	>98 (12 h)
			3	>98 (20 h)
			4	23 (24 h)
		1	1	>95 (12 h)
			2	>95 (12 h)
			3	>50 (12 h)

[a] Relative conversion rates of substrates were obtained by ^{1}H NMR spectroscopy.

times with 0.1 mol% loading, 3 times with 0.5 mol%, 6 times with 1.0 mol%, and 11 times with 2.5 mol% for substrate **19**. For the oxygen-containing diene **27** and N-protected substrates **33** and **41**, catalyst **16** is also very recyclable and high conversions were obtained. Even for cross-metathesis, catalyst **16** could be recycled and reused 3 times with 2.5 mol% loading and 2 times with 1.0 mol%. This is comparable to the results for other cation-[6a,c,d,e,f] or anion-appended[6b] ruthenium carbene catalysts. The total TON of cata-

Table 3. Recycling and reuse of **16** in BMI·PF_6 for different substrates.

Cycle	Diene	Product	Conditions[a]	Convn.[b] (yield) (%)
1	 **37**	 **38**	24 h, 80°C	>98(97)
2	 **33**	 **34**	40min, 35°C	>98(97)
3	 **39**	 **40**	24 h, 45°C	>98(97)
4	 **19**	 **20**	40min,35°C	>98(98)
5	 **43**  **44**	 **45**	12 h, 35°C	>98(95)
6	 **41**	 **42**	1 h, 35°C	>98(97)
7	 **31**	 **32**	3 h, 35°C	>98(98)
8	 **27**	 **28**	24 h, 80°C	>98(90)

[a] **16** (2.5 mol%) relative to the substrate.
[b] Relative conversion rates of substrates were obtained by ^{1}H NMR spectroscopy.

lyst **16** for substrates is reduced with increased catalyst loading. This can be attributed to decomposition of the catalyst, which was accelerated in the presence of ruthenium residues and other decomposition products. Nevertheless, **16** is a recyclable catalyst in IL for many different diene substrates.

In addition, the utilization of ferrocene-tagged catalysts is a far superior strategy to decrease the Ru contaminations in the products. Catalyst **16** dissolves in the ionic liquid *via* electrostatic interactions of the cationic ferrocene tag. At the same time, the use of an ionic liquid should make most of the Ru residue stay within the ionic liquid, which decreases the Ru residues in the products. Inductively coupled plasma-mass spectrometry (ICP-MS) analysis of product **20** after the first recycle using catalyst **16** (2.5 mol% Ru) indicates only 26.1 ppm Ru contamination in the crude products. This value is substantially lower than that obtained for homogeneous monomeric catalysts **2** or **4**, where all of the catalyst remains in the product mixture (1.0%, by mass) and this is similar to previously reported methods,[6e,10] although further purification was still needed to obtain products pure enough for medical uses.

Having established the recyclability and reusability of catalyst **16**, we next focused on its performance for RCM in a variety of other tri- and tetrasubstituted dienes as well as for cross-metathesis. As shown in

Table 3, use of 2.5 mol% of the catalyst relative to the substrate led to high conversions even for the tetrasubstituted dienes. As expected, extended reaction times and higher temperatures were necessary to achieve high conversions for the tetrasubstituted dienes. The recycled catalyst and ionic liquid from the reaction of **37** were used for the metathesis of the next substrate. The catalyst remained highly active for **27** even after being recovered 7 times. It should be noted that the crude product from **27** consisted of only the cyclic product **28** and was devoid of any detectable amount of the product from the previous reactions. This demonstrates the advantage of the sequential use of a recyclable and reusable catalyst.

This recycle system offers an easy way to recycle both the Ru catalyst and the IL and it is significantly different from traditionally redox-tagged systems. After the reaction was finished, the Ru catalyst could be easily separated from the supporting IL by just adding DMFc to reduce the cationic ferrocene and then extracting it with benzene. The recycled Ru catalyst and the IL could then be used for other purposes without any further purification. More than 81% Ru carbene **15** was recovered from a reaction system after one RCM reaction cycle. The remaining IL could be used in further reactions after simply treating it with a reducing reagent, and extracting it with benzene to remove the ferrocenes. This new strategy using redox chemistry to control the immobilization and to recycle both the catalyst and the IL offers a new step toward the ideal catalyst.

Conclusions

A ferrocene-tagged Ru carbene, which can be reversibly dissolved in an IL by varying the ferrocene tag *via* redox reactions, has been developed. Given the growing interest in the development of recyclable catalytic systems for different tasks in organic synthesis, the ferrocene tagging strategy described here could be applied to the design of other transition-metal-based catalysts.

Experimental Section

Synthesis of (*E*)-[4-Isopropoxy-3-(prop-1-enyl)-phenyl]methanol (12)

A flask was charged with 1.50 g (5.91 mmol) (*E*)-4-bromo-1-isopropoxy-2-(prop-1-enyl)-benzene (precursor for **12**) and 5 mL anhydrous diethyl ether. The solution was cooled to −78 °C, and 4.27 mL *n*-BuLi (1.66 M in hexanes, 7.08 mmol, 1.2 equiv.) was slowly added *via* a syringe. The reaction mixture was then allowed to warm to room temperature slowly. After being stirred for 1 h at room temperature, the reaction mixture was cooled to −78 °C. To this mixture, 0.43 g DMF (5.91 mmol, 1 equiv.) was added slowly *via* a syringe. The resulting solution was stirred for 1 h at this temperature. The mixture was then concentrated under vacuum to obtain a thick oily residue. A 20 mL portion of dichloromethane was added to this residue. After being washed four times with water, the organic layer was dried over magnesium sulfate. Removal of the solvent from the filtration gave an oily residue. The residue was then dissolved in 15 mL methanol, and then 0.48 g $NaBH_4$ (12.7 mmol, 2.5 equiv.) were added. The mixture was stirred for 5 h at room temperature, and was then concentrated under vacuum to give a colourless residue. Next, 20 mL of water and 100 mL of dichloromethane were added to the residue. The organic layer was separated and washed four times with water, dried over magnesium sulfate, filtered and concentrated. The residue was purified by silica gel chromatography using dichloromethane as the eluant. The desired (*E*)-[4-isopropoxy-3-(prop-1-enyl)phenyl]methanol (**12**) was obtained as a colourless oil; yield: 0.86 g (4.20 mmol, 71%); analytical data: found (calcd) for $C_{13}H_{18}O_2$: C 75.60 (75.69), H 8.70 (8.80); ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.35$ (d, $^3J_{H,H} = 6.0$ Hz, 6H, C*H*$_3$), 1.90 (dd, $^3J_{H,H} = 1.6$, $^3J_{H,H} = 6.8$ Hz, 3H, C*H*$_3$), 2.84 (s, 1H, O*H*), 4.47 (m, $^3J_{H,H} = 6.0$ Hz, 1H, C*H*), 4.53 (s, 2H, C*H*$_2$), 6.208 (m, 1H, $^3J_{H,H} = 6.8$ Hz, =C*H*), 6.71 (dd, $^3J_{H,H} = 1.6$, $^3J_{H,H} = 16$ Hz, C*H*ar), 6.81 (d, 1H, $^3J_{H,H} = 8.4$ Hz, =C*H*), 7.08 (dd, $^3J_{H,H} = 2.0$ Hz, $^3J_{H,H} = 8.4$ Hz, 1H, C*Har*), 7.38 (d, $^3J_{H,H} = 2$ Hz, 1H, C*H*ar); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 19.2$, 22.4, 65.0, 71.3, 114.7, 125.7, 126.1, 126.3, 126.8, 128.5, 133.5, 154.3; IR (CH_2Cl_2): $\nu = 3395$, 3035, 2977, 2932, 2728, 2650, 1651, 1608, 1492, 1448, 1378, 1245, 1120, 1020, 967, 816, 623, 631, 519, 469 cm^{-1}.

Preparation of 4-Ferrocenebutyric Acid (13)

A solution of ferrocene (4.4 g, 23.4 mmol) and succinic anhydride (2.34 g, 23.4 mmol) in dry CH_2Cl_2 (40 mL) was added drop wise to a mixture of $AlCl_3$ (8.5 g, 64.4 mmol) and dry CH_2Cl_2 (40 mL) at 0 °C under N_2. After being stirred for 2 h at 0 °C, the reaction mixture was poured into ice and extracted with CH_2Cl_2 to remove the unreacted ferrocene. The aqueous layer was acidified with hydrochloric acid to give an orange crystalline precipitation of 4-ferrocenyl-4-oxobutyric acid; yield: 4.5 g (73.5%).

Within 15 min, Zn-amalgam (30.1 g, containing 5% Zn) was added in small portions to a solution of 4-ferrocenyl-4-oxobutyric acid (4.0 g, 11.6 mmol) in cold AcOH (80 mL). The reaction mixture was stirred at 90–100 °C for 1.5 h, and then the liquid part of the reaction mixture was poured into water, and extracted with ethyl ether. The obtained organic layer was washed with a saturated solution of NaCl, and dried with anhydrous $MgSO_4$. Orange crystals of 4-ferrocenebutyric acid **13** were obtained after evaporation of the solvent; yield: 1.41 g (5.18 mmol, 37%); analytical data found (calcd.) for: $C_{14}H_{16}O_2Fe$: C 61.91 (61.79), H 5.94 (5.93); ^1H NMR (500 MHz, $CDCl_3$): $\delta = 1.85$ (t, $^3J_{H,H} = 9.0$ Hz, 2H, C*H*$_2$), 2.39 (t, $^3J_{H,H} = 9.0$ Hz, 4H, C*H*$_2$), 4.07 (d, $^3J_{H,H} = 4.0$ Hz, 4H, Fc*H*), 4.12 (s, 5H, Fc*H*); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 26.2$, 29.1, 34.0, 67.6, 68.4, 68.8, 88.2, 180.6: IR (KBr): $\nu = 3095$, 2949, 2917, 2855, 1713, 1455, 1433, 1410, 1329, 1276, 1220, 1185, 1103, 1036, 1001, 911, 818, 702, 485, 415 cm^{-1}.

Preparation of the Ferrocene-Tagged Ligand 14

To a solution of (*E*)-[4-isopropoxy-3-(prop-1-enyl)phenyl]-methanol (0.15 g, 0.73 mmol) and 1-ferrocenebutyric acid (0.24 g, 0.73 mmol) in anhydrous CH_2Cl_2, DCC (0.15 g, 0.73 mmol) and DMAP (0.178 g, 1.46 mmol) were added at 0 °C. After being stirred for 1 h at 0 °C, the mixture was stirred for 12 h at room temperature. Then, the insoluble materials were filtered out to obtain a clear filtrate. Removal of the solvent from the filtrate under vacuum gave a crude product of **14**. Pure **14** was obtained as yellow oil after flash column chromatography purification of the crude product on silica using pentanes/CH_2Cl_2 (1:1) as the eluant; yield: 0.26 g (0.51 mmol, 70%); analytical data found (calcd.) for $C_{27}H_{32}O_3Fe$: C 70.57 (70.44), H 7.02 (7.01). ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.34$ (d, $^3J_{H,H} = 7.5$ Hz, 6 H, CH_3), 1.84 (d, $^3J_{H,H} = 8.5$ Hz, 3 H, CH_3), 1.89 (d, $^3J_{H,H} = 7.5$ Hz, 2 H, CH_2), 2.34 (m, $^3J_{H,H} = 5.0$ Hz, 4 H, CH_2), 4.04 (s, 4 H, Fc*H*), 4.04 (s, 5 H, Fc*H*), 4.53 (m, $^3J_{H,H} = 7.5$ Hz, 1 H, C*H*), 5.04 (s, 2 H, CH_2), 6.22 (m, $^3J_{H,H} = 8.5$ Hz, 1 H, =C*H*), 6.68 (d, $^3J_{H,H} = 20$ Hz, 1 H, =C*H*), 6.81 (d, $J_{H,H} = 10.5$ Hz, 1 H, C*H*ar), 7.13 (d, $^3J_{H,H} = 10.5$ Hz, 1 H, C*H*ar), 7.41 (s, 1 H, C*H*ar); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 19.2$, 22.5, 26.5, 29.2, 34.2, 66.4, 67.6, 68.5, 68.9, 71.057, 88.5, 114.2, 125.9, 126.6, 127.3, 128.2, 128.3, 128.5, 154.9, 173.7; IR (CH_2Cl_2): $\nu = 3088$, 2975, 2932, 1733, 1609, 1498, 1447, 1378, 1245, 967, 817, 683, 497, 463, 436, 410 cm^{-1}.

Preparation of the Ferrocene-Tagged Catalyst 15

To a flask charged with Grubbs' catalyst **2** (0.42 g, 0.50 mmol) and CuCl (0.05 g, 0.50 mmol), a solution of **14** (0.30 g, 0.6 mmol) in 25 mL dry dichloromethane was added at room temperature under N_2. The resulting mixture was then refluxed for 20 min. After being cooled down to room temperature, the reaction mixture was filtered to collect a clear filtrate. The solvent from the filtrate was evaporated under vacuum to give a residue. The residue was purified by flash column chromatography on silica using CH_2Cl_2 as the elutant to give the desired product **15** as a green crystalline solid; yield: 0.32 g (0.34 mmol, 68%); analytical data found (calcd.) for $C_{46}H_{54}Cl_2N_2O_3FeRu$: C 60.81 (60.66), H 5.98 (5.98), N 3.09 (3.08); ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.26$ (d, $^3J_{H,H} = 6.5$ Hz, 6 H, 2 CH_3), 1.82 (d, $^3J_{H,H} = 7.5$ Hz, 2 H, CH_2), 2.34 (m, $^3J_{H,H} = 7.5$ Hz, 4 H, CH_2), 2.41 (s, 6 H, CH_3), 2.47(s, 12 H, CH_3), 4.07 (s, 4 H, Fc*H*), 4.12 (s, 5 H, Fc*H*), 4.18 (s, 4 H, CH_2), 5.07 (s, 2 H, CH_2), 4.87 (m, $^3J_{H,H} = 6.5$ Hz, H, C*H*), 6.76 (d, $J_{H,H} = 8.5$ Hz, H, C*H*ar), 6.91 (s, 1 H, C*H*ar), 7.07 (s, 4 H, C*H*ar), 7.50 (dd, $^3J_{H,H} = 2.0$ Hz, $^3J_{H,H} = 8.5$ Hz, 1 H, C*H*ar), 16.52 (s, 1 H, Ru-*H*); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.3$, 21.4, 26.3, 29.2, 29.9, 34.2, 51.7, 51.8, 51.8, 65.4, 68.1, 69.0, 69.5, 75.6, 89.3, 13.1, 123.2, 129.6, 129.9, 130.0, 130.3, 135.7, 139.1, 145.4, 152.4, 173.5, 211.0, 296.1; IR (KBr): $\nu = 3091$, 2924, 2864, 2738, 1891, 1734, 1670, 1595, 1486, 1446, 1425, 1384, 1262, 1133, 1105, 1032, 930, 855, 819, 757, 579, 544, 497, 442 cm^{-1}.

Cyclic Voltammogram of the Ferrocene-Tagged Catalyst 15

Cyclic voltammetry (CV) was carried out in a standard one-compartment cell under a nitrogen atmosphere at 25 °C using a platinum-wire counter electrode and an SCE reference electrode with a BAS Epsilon voltammetric analyzer (scan rate 50 mV/s). Before each experiment the electrodes were washed in ultrapure water containing a protein remover for 5 min and then sonicated in ultrapure water and acetone for 5 min. The CV spectra were obtained by a linear scan from −0.3 to 1.5 V *vs.* SCE in a solution of catalyst **15** (10^{-3} M) in 0.1 M electrolyte (Bu_4NClO_4-CH_2Cl_2). The results are shown in Figure 1.

Preparation of the Cationic Ferrocene-Tagged Ruthenium Complex (16)

A solution of catalyst **15** (0.30 g, 0.33 mmol) in dry dichloromethane (10 mL) was added to a flask under N_2. A solution of I_2 (43.2 mg, 0.17 mmol, 0.5 equiv.) in dry dichloromethane (5 mL) was added slowly to the reaction mixture *via* a syringe at room temperature. The resulting mixture was then stirred for 10 min. Removal of the solvent from the reaction mixture under vacuum gave a green solid. The ruthenium complex **16** was obtained by chromatographic purification of the residue using CH_2Cl_2/ethyl acetate (2:1) as the eluant; yield: 0.31 g (0.30 mmol, 90%); analytical data found (calcd.) for $C_{46}H_{54}Cl_2N_2O_3FeRuI$: C 53.28 (53.24), H 5.24 (5.25), N 2.69 (2.70); ^{1}H NMR (500 MHz, $CDCl_3$: $\delta =$ −6.64~-4.55 (Fc*H*), 0.77 (6 H, 2 CH_3), 0.86 (2 H, CH_2), 1.26 (6 H, 2 CH_3), 1.44 (2 H, CH_2), 2.06 (12 H, 4 CH_3), 2.27 (2 H, CH_2), 3.91 (4 H, CH_2), 4.56 (2 H, CH_2), 6.10 (1 H, C*H*ar), 7.23 (1 H, C*H*ar), 7.34 (1 H, C*H*ar), 15.49 (1 H, Ru-*H*); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 64.8$, 74.5, 112.4, 121.3, 129.6, 129.9, 142.7, 150.2, 171.0, 171.0, 208.3; ESI-MS: $m/z =$ 1059.6 $[M+Na]^+$ (calcd.: 1060.08); +c ESI-MS: $m/z = 910.12$ $[C_{46}H_{54}Cl_2N_2O_3RuFe]^+$ (calcd.: 910.19); −c ESI-MS: $m/z =$ 127.16 (calcd.: 126.90).

Reduction Study of the Ruthenium Carbene Complex 16

To a solution of catalyst **16** (0.10 g, 0.1 mmol) in dry dichloromethane (5 mL), bis(pentamethylcyclopentadienyl)-iron (65.2 mg, 0.2 mmol, 2 equiv.) was added at room temperature under N_2. The resulting mixture was then stirred for 10 min. Removal of solvent from the reaction mixture under vacuum gave a dark green solid. Ruthenium complex **15** was obtained by chromatographic purification of the residue using CH_2Cl_2 as the eluant; yield: 0.082 g (0.09 mmol, 90%); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.25$ (d, $^3J_{H,H} = 6.0$ Hz, 6 H, 2 CH_3), 1.77 (d, $^3J_{H,H} = 1.6$ Hz, 2 H, CH_2), 2.34 (m, $^3J_{H,H} = 7.2$ Hz, 4 H, CH_2), 2.41 (s, 6 H, CH_3), 2.47 (s, 12 H, CH_3), 4.18 (s, 4 H, Fc*H*), 4.20 (s, 5 H, Fc*H*), 4.24 (s, 4 H, CH_2), 4.88 (m, $^3J_{H,H} = 5.6$ Hz, 1 H, C*H*), 5.07 (s, 2 H, CH_2), 6.76 (d, $J_{H,H} = 8.4$ Hz, 1 H, C*H*ar), 6.90 (s, 1 H, C*H*ar), 7.07 (s, 4 H, C*H*ar), 7.50 (dd, $^3J_{H,H} = 1.2$ Hz, $^3J_{H,H} = 8.2$ Hz, 1 H, C*H*ar), 16.51 (s, 1 H, Ru-*H*); ESI-MS: $m/z = 910.2$ $[M]^+$ (calcd. for $[C_{46}H_{54}Cl_2N_2O_3FeRu]^+$: 910.19).

Shuttling of 15 between the IL and Organic Phase by Switching On and Off the Ferrocene Tag Monitored with UV/Vis Spectroscopy

Under N_2 gas, a glass vial with a screw-cap top was charged with 3.0 mg (0.0033 mmol) **15**, 0.50 mL CH_2Cl_2/benzene (1:10), and 0.20 mL $BMIPF_6$. The resulting mixture was shaken at room temperature. After 15 min, 10.0 μL aliquots were taken from the upper organic layer using a microsyringe and were diluted to 10.0 mL with CH_2Cl_2. The resulting solutions were subjected to UV detection. The concentration of **15** in the organic layer was obtained by comparing the absorption value with a standard solution of **15**. I_2 (0.42 mg, 0.0017 mmol, 0.5 equiv.) was then added to the mixture and the resulted mixture was shaken at room temperature for 10 min. Aliquots (10 μL) were taken from the upper organic layer, and subjected to UV detection. Next, 1.1 mg (0.0033 mmol, 1 equiv.) bis(pentamethylcyclopentadienyl)iron was introduced into the vial and the resulting mixture was shaken at room temperature for a few minutes. Aliquots (10 μL) were again taken from the upper organic layer to detect the concentration of **15**. The operation was repeated 4 times and the concentration changes of **15** in the upper organic layer are shown in Figure 2.

Kinetics Study of 15 and 16

A Schlenk flask was charged with catalyst (0.012 mmol, 1.0 mol%) and CH_2Cl_2 (12.0 mL). The sample was equilibrated at 30 °C before **17** (289.5 μL, 288 mg, 1.2 mmol, 0.1 M) was added *via* a syringe. Aliquots were taken from the reaction mixture at appropriate times using a syringe and were quenched immediately with 0.1 mol/L PEI in CH_2Cl_2. The resulting solution was then subjected to short column chromatography to remove the Ru metal residue using CH_2Cl_2 as the eluant. Solvent from the collected solution was evaporated under vacuum. The conversion to **17** was determined by comparing the ratio of the integrals of the methylene proton peaks in the starting material, $\delta = 2.63$ (dt), with those in the product, $\delta = 3.01$ (s). The result is shown in Figure 3.

Catalytic Study of the Ruthenium Carbenes 15 and 16

The general procedure for metathesis reactions with the ruthenium carbene **15** and **16** is performed as follows: a certain amount of ruthenium carbene catalyst **15** (or **16**) and a solution of substrate in dry CH_2Cl_2 or toluene was mixed in a reaction flask under nitrogen. The reaction mixture was stirred for 0.5–24 h. At the end of the reaction (monitored by TLC), the catalysts were separated by silica gel chromatography using CH_2Cl_2 as the eluant to remove trace amounts of Ru residues. Conversions were estimated by ‘H NMR spectroscopy and obtained by comparing the ratios of the integrals of the starting materials with those of products. The catalytic activities of ruthenium carbene **15** and **16** for a variety of substrates are shown in Table 1.

Recycle Study of the Ruthenium Carbene 16 in IL

The general procedure for metathesis reactions with **16** in IL was performed as follows: catalyst **16** (2.5 mol%, 1.0 mol%, 0.5 mol%, or 0.1 mol% Ru), and 0.04 mL BMI PF_6 in dry CH_2Cl_2 (0.5 mL) were mixed in a reaction flask under N_2. After the complete transfer of **16** from the organic phase to the ionic phase, substrate (0.13 mmol) was introduced to the solution of **16**. The reaction mixture was stirred at 35 °C until the conversion of substrate was completed (monitored by TLC). Then the solvent was removed under vacuum and petroleum ether was added. The mixture was subjected to centrifugation to separate the ionic layer (containing **16**). The ionic layer (containing **16**) was then subjected to another cycle. Solvent from the organic solution was evaporated to afford the crude cyclized product. After purification by short column chromatography to remove trace amounts of Ru residue, the sample was subjected for ^{1}H NMR. Conversions were obtained by comparing the ratios of the integrals of starting materials with those of products. The recycle data for **16** are shown in Table 2.

Sequential Use of Catalyst 16 in the RCM of Different Substrates

3.4 mg (0.0033 mmol) **16**, and 0.04 mL $BMI{\cdot}PF_6$ in dry CH_2Cl_2 (0.5 mL) were mixed in a reaction flask under N_2. After the solution had been stirred for 5 min, substrate (0.13 mmol) was introduced into this solution *via* a syringe. The reaction mixture was stirred at different temperature until the reaction was completed (monitored by TLC). Then, CH_2Cl_2 from the solution was removed under vacuum and petroleum ether was added. The mixture was subjected to centrifugation to separate the ionic layer (containing **16**). The ionic layer (containing **16**) was then subjected to another cycle. Solvent from the organic solution was evaporated to afford the crude cyclized product. After purification by short column chromatography to remove trace amounts of Ru residue, the sample was subjected to ^{1}H NMR analysis. Conversions were obtained by comparing the ratios of the integrals of starting materials with those of products. The recycle data for **16** are shown in Table 3.

Recovery of the Ru Catalyst 15 and the IL

The general procedure for metathesis reactions with **16** in IL is as described above. When the conversion of the substrate was completed, the product was removed as described above. To the separated ionic layer (containing **16**), a solution of DMFc (one equiv.) in dry dichloromethane (0.5 mL) was added at room temperature under N_2. The resulting mixture was then stirred for 30 min. After the CH_2Cl_2 from the mixture had been removed under vacuum, the residue was repeatedly washed with benzene (1 mL/each). The removal of solvent from the combined benzene layers gave the ruthenium complex **15**; yield: 2.4 mg (0.0030 mmol, 81%).

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