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Synthetic and mechanistic studies on enyne metathesis: A catalyst influence

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Dedicated to Professor Bogdan Marciniec on the occasion of his 65th birthday anniversary, in acknowledgement of his significant contributions to organic and organometallic chemistry.

Abstract

We have investigated the selectivity of the intramolecular enyne metathesis catalyzed by representative first- and second-generation ruthenium carbenes. This study witnesses the very subtle and cooperative influence of different parameters on the stereochemical course of this reaction. In the case of enynes containing an internal triple bond and a monosubstituted double bond only the application of first-generation catalysts leads selectively to the formation of the expected product. If the substrate bears an internal triple bond and a 1,1-disubstituted alkene fragment first-generation catalysts are inert in this cyclization, while in the case of more reactive second-generation catalysts the transformation proceeds with high conversion, but is not selective. Only when a substrate contains a less accessible (e.g. sterically hindered) triple bond the application of second-generation catalysts can ensure a high level of selectivity.

Keywords: Enyne metathesis; Ruthenium; Catalysis; Selectivity

1. Introduction

Enyne metathesis has become an important synthetic method. Recent reviews have described the synthetic utility and mechanistic aspects of this reaction in detail [1–3]. The metathesis between an alkyne and an alkene provides a conjugated 1,3-diene (Scheme 1).

Like its sister transformation olefin metathesis, enyne metathesis has seen many applications in organic synthesis and is increasingly used in total synthesis of complicated bioactive or natural products [4]. This is due to the discovery of well-defined alkylidene-metal catalysts of which the ruthenium carbenes bearing types **1**, **2** and **2′** ligands offer a good compromise between efficiency and tolerance toward functional groups (Scheme 2) [5].

2. Discussion

In the course of our investigation on the reactivity profile of new Hoveyda type catalysts **N1** and **N2** [9], we observed that the use of second-generation complexes **H2**, **N2** and **A2** in enyne metathesis led in some cases to the formation of an undesired product and, thereby resulting in a low selectivity for this process. Interestingly, the first-generation congener **N1** exhibited a high level of selectivity in this transformation, leading to the formation of a single product [9]. Recently, Mori and co-workers have shown that metathesis of enynes containing an internal triple bond and a 1,1-disubstituted alkene unit proceed in a non-selective manner, leading to the formation of three products: an expected five-membered ring product **4**, a six-membered ring product **5** and a bicyclic product **6**, containing a cyclopropane unit (Scheme 3, $X \neq H$) [10a,b]. However, when a substrate having a monosubstituted alkene ($X = H$) was treated with **G1** in a similar manner, the cyclized product **4** was obtained selectively in high yield [10c].

We decided to investigate in detail the respective influences of substrate's and catalyst's nature on the course of this transformation [11]. To do so, we were led to synthesize a range of enynes bearing different substitutents in hope to observe possible regularities.

Our exploratory study (Scheme 4; Table 1) starts from a simple substrate bearing an internal C–C triple bond and a monosubstituted alkene fragment (**3a**). In reactions catalyzed by second-generation carbenes (both Grubbs' and Hoveyda's type)

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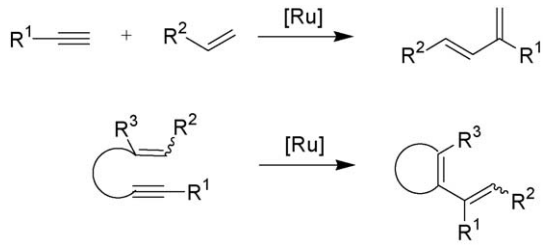
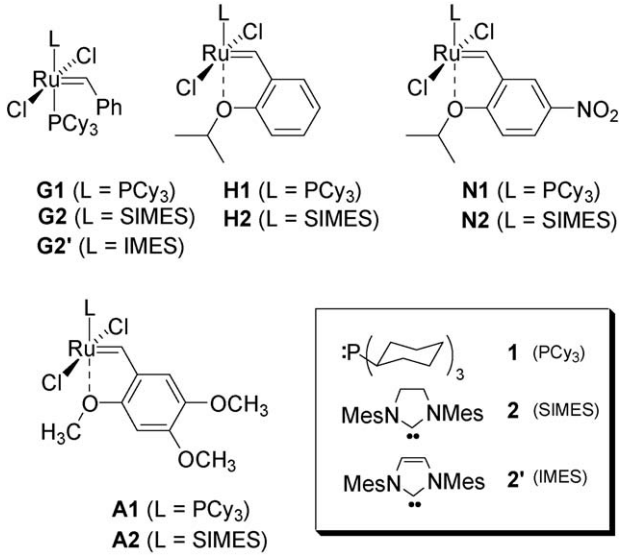


Scheme 1. Enyne metathesis.



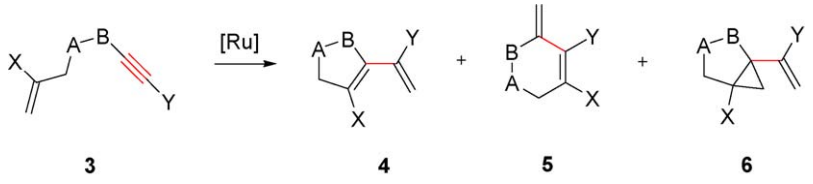
Scheme 2. Modern ruthenium catalysts for olefin and enyne metathesis. **G**: Grubbs [5], **H**: Hoveyda–Grubbs [6], **N**: nitro-Hoveyda–Grubbs [7] and **A**: Asarone catalysts [8] (Mes = 2,4,6-trimethylphenyl, Cy = cyclohexyl).

an inseparable mixture of **4a**, **5a** and **6a** was formed (Table 1, entry 1). The ratio of products was calculated from GC–MS and NMR spectra, while the products were identified by means of NMR and GC–MS spectra analysis and comparison with authentic samples, where available. Interestingly, first-generation catalysts give only one product, **4a**. Similar results were obtained in the case of other substrates containing an internal alkyne motif (**3b**, **3c**, **3d**, **3e** and **3f**). In all cases the use of first-generation ruthenium catalysts led to selective formation of only one product (**4**), while second-generation complexes were in general less selective. It should be noted that in the case of **3c**, a cyclopropane derivative of type **6** was not formed, whereas in the case of **3f**, we did not observe a six-membered product **5f**. After analyzing the data compiled in Table 1 one can arrange the catalysts in the following order of increasing selectivity:

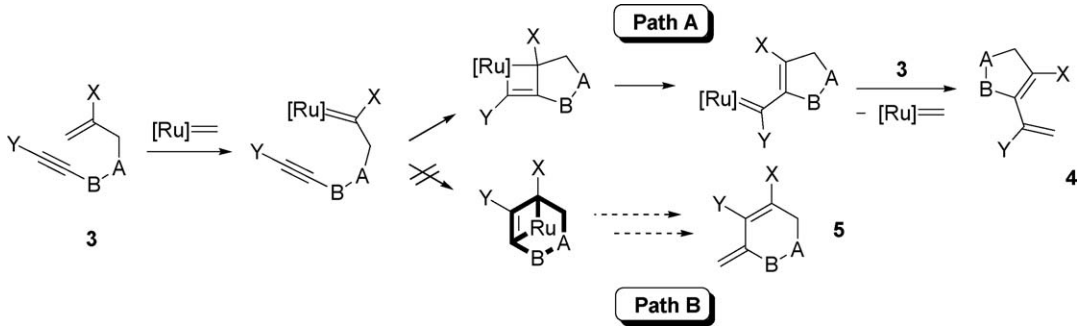
$$\mathbf{N2 < H2 < G2 \approx G2' << A1 = H1 = N1 = G1} \quad (\textit{selectivity} \rightarrow)$$

Encouraged by these results, we decided to undertake a similar investigation of "Mori's type" enynes bearing an internal alkyne and a 1,1-disubstituted alkene fragment [10a,b]. In the case of enyne **3g**, two products **4g** and **5g** were formed in almost equal amounts (together with 1–5% of **6g**) using second-generation catalysts. In line with previous observation [10a], in the case of first-generation catalyst the reaction did not proceed at all (Table 1, entry 7).

Analysis of the conversion and selectivity rates yielded some interesting findings. Based on these results, we tried to explain the respective roles of the catalyst and substitution pattern of the enyne substrate on the course of this reaction. In general, two major pathways can be proposed for those substrates: "ene-then-yne", features cases where the cycloaddition to a double bond occurs first, and "yne-then-ene", those where prior addition to a triple bond takes place [10–12]. Perfect selectivity of first-generation catalysts may indicate that in this case the reaction proceeds according to path A, namely via cycloaddition of a ruthenium–carbene to the double bond followed by [2 + 2] cycloaddition to the triple bond, to form the sole five-membered ring product



Scheme 3. Enyne metathesis of substrates bearing a 1,1-disubstituted alkene unit [10a,b].



Scheme 4. Ene-then-yne pathway (cycloaddition to a double bond first).

(Scheme 4). Path B is not possible due to formation of a highly strained bicyclic intermediate during the initial cycloaddition step (Scheme 4).

Since dissociation of the phosphane ligand in **G1**, leading to the formation of catalytically active 14-electron species, occurs faster than dissociation of the chelating isopropoxy fragment in Hoveyda's complexes, therefore Grubbs I catalyst **G1** initiates faster than Hoveyda's I-generation complexes [6,13]. On the other hand, it is known that 1,1-disubstituted alkenes do not react with first-generation metathesis catalysts [14], and for this reason the reaction of substrate **3g**, where X = CH_3 catalyzed by carbenes **G1**, **A1**, **H1** and **N1**, does not proceed. Formation of **4g** and **5g** in equal amounts in the presence of **1a–d** means that this reaction runs through paths C and D via addition to the triple bond (Table 1, entry 7).

Also in other reactions of this type tested by us, second-generation catalysts gave usually mixtures of two major products **4** and **5**. It means that, in that case, the reaction proceeded through pathways C and D. One exception is the reaction of **3f**, where product **5f** was not formed, even when the less selective second-generation catalyst **N2** was used. We presume that, in this case, the steric hindrance of two phenyl groups prohibits the interaction between the ruthenium carbene and the triple bond. Products of type **6** are known to be formed in the path C via reductive elimination from metalacyclobutane derivative [10] or through "enyne bond reorganization" [15] and we, indeed,

Table 1
Reaction of enynes containing internal triple bond

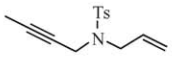
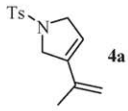
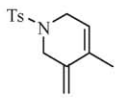
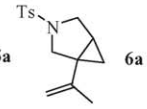
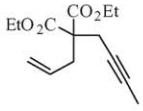
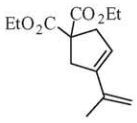
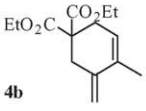
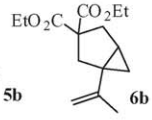
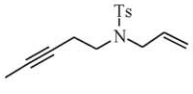
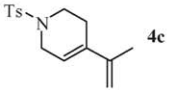
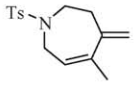
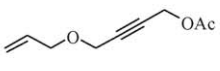
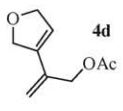
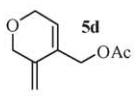
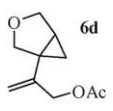
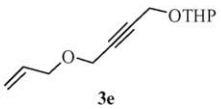
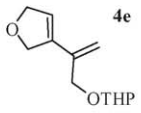
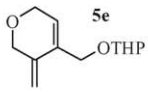
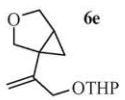
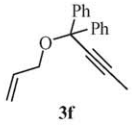
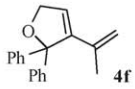
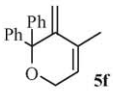
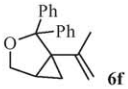
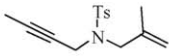
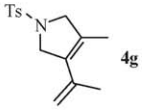
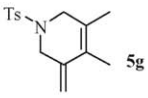
Run	Substrate	Conditions	Yield, %[a]	Products (ratio, %)		
	 **3a**	CH_2Cl_2 25°C 2.5 % mol (catalyst)		 **4a**	 **5a**	 **6a**
1	A = NTs, B = CH_2 X = H, Y = CH_3	**G2**, 2h	72	94	5	1
		G2', 2h	74	95	3	2
		H2, 1.5h	59	87	7	4
		N2, 1h	87	83	14	3
		A1, 2h	97	100	-	-
		H1, 3.5h	89	100	-	-
		N1, 1.5h	92	100	-	-
	 **3b**	CH_2Cl_2 25°C 5 % mol (catalyst)		 **4b**	 **5b**	 **6b**
2	A = $C(CO_2Et)_2$ B = CH_2 X = H, Y = CH_3	**G2**, 2h	90	95	5	-
		H2, 3h	(96)	93	6	1
		N2, 1h	88	81	11	8
		G1, 20h	(97)	100	-	-
		H1, 24h	(34)	100	-	-
		N1, 24h	(75)	100	-	-
	 **3c**	CH_2Cl_2 25°C 2.5 % mol (catalyst)		 **4c**	 **5c**	
3	A = NTs, B = CH_2-CH_2 X = H, Y = CH_3	**G2**, 2.5 h	(100)	93	7	
		N2, 0.25h	(100)	88	12	
		G1, 4h	(93)	100	-	
		N1, 20h	(93)	100	-	
	 **3d**	CH_2Cl_2 25°C 2.5 % mol (catalyst)		 **4d**	 **5d**	 **6d**
4	A = O, B = CH_2 X = H, Y = CH_2OAc	**N2**, 1h	78	76	20	4
		N1, 1h	94	100	-	-

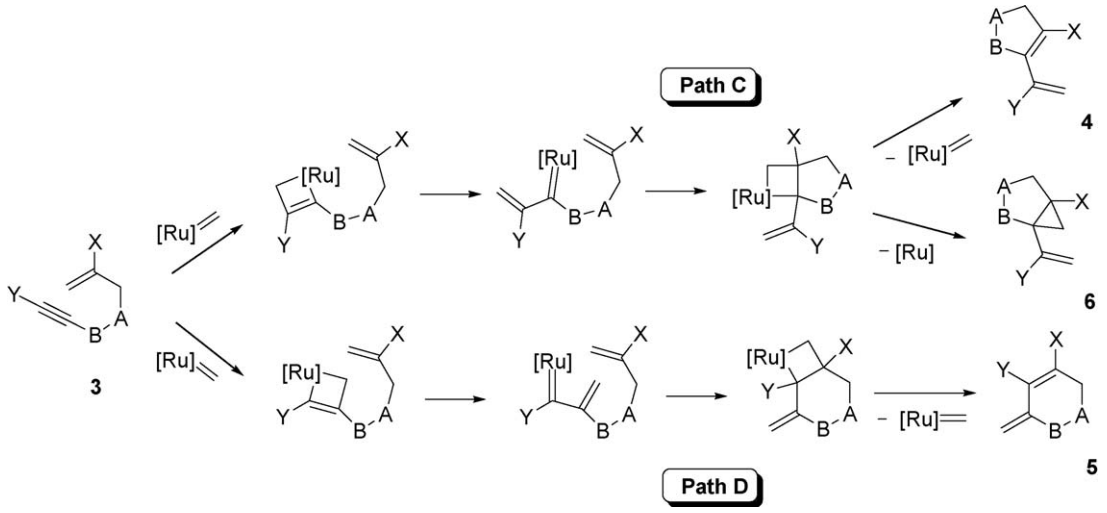
Table 1 (*Continued*)

5	 **3e**	CH_2Cl_2, 25°C, 2.5 % mol (catalyst)		 **4e**	 **5e**	 **6e**
	A = O, B = CH_2 X = H, Y = CH_2OTHP	**G2**, 4h **H2**, 5h **N2**, 1.5h **N1**, 6h	42 25 50 73	not determined (decomposition) 88 80 100	 7 16 -	 5 4 -
6	 **3f**	CH_2Cl_2, reflux, 5 % mol (catalyst)		 **4f**	 **5f**	 **6f**
	A = O, B = $C(Ph)_2$ X = H, Y = CH_3	**N2**, 1h **N1**, 20h	94 91	98 100	- -	2 -
7	 **3g**	CH_2Cl_2, reflux, 5 % mol (catalyst)		 **4g**	 **5g**	
	A = NTs, B = CH_2 X = CH_3, Y = CH_3	**G2**, 20h **G2'**, 20h **H2**, 24h **N2**, 24h **G1**, **A1**, **H1**, **N1**, 24h	38 32 (82) (100) 0	47 53 50 56 -	53 47 50 44 -	

[a]Isolated yields after silica gel chromatography. In parentheses are GC or NMR conversions.

observed such products in many reactions catalyzed by second-generation complexes.

NHC ligands **2** and **2′** are better σ-donors as compared to PCy_3 and, as a result, NHC–ruthenium carbenes feature lower energetic barriers in cycloaddition–insertion reactions [12]. While this should not be over-interpreted, this would seem to indicate that [2 + 2] cycloaddition to the triple bond (paths C and D) which can give a six-membered ring product **5** and a cyclopropane derivative **6** (Scheme 5) is favorable in the case of second-generation catalysts. Nevertheless, the path A is still operative, with **4** being formed as a major reaction product in most cases. Since the kinetically controlled cycload-



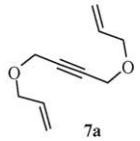
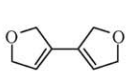
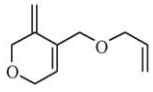
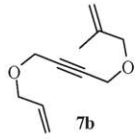
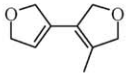
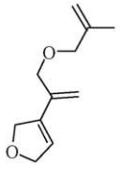
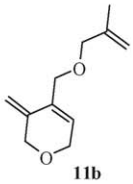
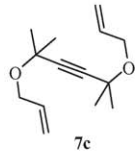
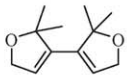
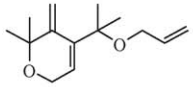
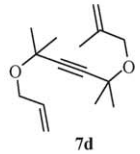
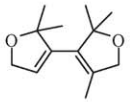
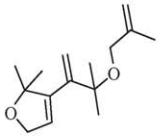
Scheme 5. Yne-then-ene pathway (cycloaddition to a triple bond first).

dition to the triple bond is determining the regioselectivity of the whole process, the most active catalyst **N2** shows the lowest selectivity.

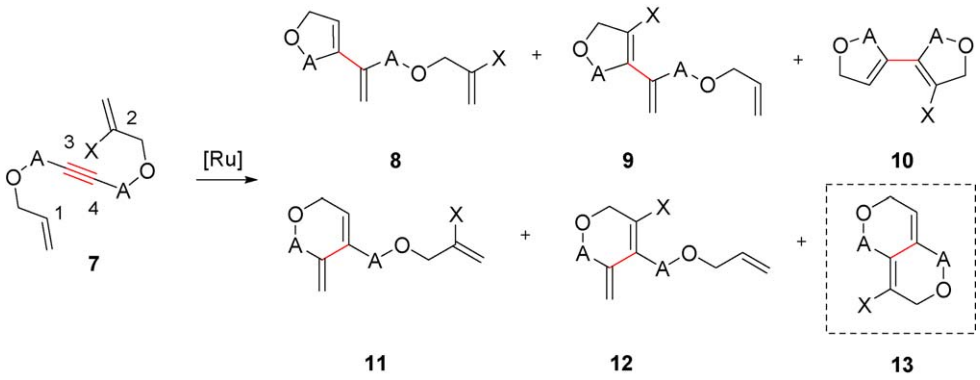
In order to further confirm our hypothesis, we studied cascade enyne-RCM transformations of type **7** substrates (Scheme 6; Table 2). As expected, only one product, **10a**, was formed using catalysts **G1** and **N1**. Product **8a** (**9a**) was not observed because it readily cyclizes to **10a** under the reaction conditions. Product **11a** (**12a**) is formed in the presence of second-generation catalysts via path D and further does not transform to condensed bicyclic product, perhaps, due to strain nature of **13**. Products **10a** and **11a** (**12a**) differ by polarities and it was possible to separate them by column chromatography.

In the case of **7b**, explaining the observed selectivity control becomes more complicated. With catalysts **G1** and **N1** dihydrofurane **8b** was obtained as a main product together with a small amount of **10b**. One can assume that at first a new ruthenium–carbene was produced on the easiest accessi-

Table 2
Cascade enyne-RCM metathesis

Run	Substrate	Conditions	Products (yield[a], %)		
1	 **7a**	CH_2Cl_2, 25°C, 2.5 % mol (catalyst)	 **10a**	 **11a**	
	A = CH_2, X = H	**H2**, 24h	51	8	
		N2, 24h	55	20	
		G1, 5min	97	-	
		N1, 24h	(100)	-	
2	 **7b**	CH_2Cl_2, 25°C, 2.5 % mol (catalyst)	 **10b**	 **8b**	 **11b**
	A = CH_2, X = CH_3	**G2**, 1h	23	-	14
		N2, 0.5h	14	-	25
		G1, 5min	3	64	-
		N1, 1h	12	29	-
3	 **7c**	CH_2Cl_2, 25°C, 2.5 % mol (catalyst)	 **10c**	 **11c**	
	A = $C(CH_3)_2$, X = H	**G2**, 2h	95	-	
		N2, 1h	95	-	
		G1, 2h	92	-	
		N1, 5h	(41)	-	
4	 **7d**	CH_2Cl_2, 25°C, 2.5 % mol (catalyst)	 **10d**	 **8d**	
	A = $C(CH_3)_2$, X = CH_3	**G2**, 24h	(83)	-	
		N2, 24h	67	-	
		G1, 24h	-	traces	
		N1, 24h	-	traces	

[a]Isolated yields after silica gel chromatography. In parentheses are GC conversions.



Scheme 6. Tandem enyne-RCM transformations.

ble monosubstituted double bond (C-1, for relative numbering of atoms refer to Scheme 6), whereas cycloaddition to the triple bond (C-3,4) proceeded with further opening of a metalacyclobutene ring to give a next metal–carbene which can hardly react with 1,1-disubstituted alkene part (C-2). This can explain why first-generation complexes **G1** and **N1** give mostly product **8b**. When the more reactive NHC-containing catalysts **G2** and **N2** are used, metal–carbenes formed from a triple bond (C-3/4) can more effectively react with a substituted C–C double bond to give **10b**. In that case, however, the initial cycloaddition step to a triple bond is also possible, leading to the formation of a six-membered heterocycle **11b** as the sole product. The preference for the formation of **11b** over **12b** corroborates the assumption that the ruthenium–carbene formed at C-4 reacts more readily with a double bond (C-1) than the ruthenium–carbene at C-3 reacting with alkene part (C-2), respectively. (In that case, it reacts with C-1 affording **10b** through intermediate **8b**.)

In the case of **7c** only **10c** is produced due to sterical hindrance of a triple bond that makes impossible approaching of ruthenium carbene to the alkyne part (C-3/4). Products **8c** and **9c** do not form since the intermediate ruthenium–carbene (formed at C-3/4) easily inserts into the double bond (C-1 and C-2) affording **10c** irrespectively of the catalyst used. Similarly, in the case of **7d** the reaction also proceeds via path A. Second-generation catalysts **G2** and **N2** give only one product, **10d**, while less active first-generation analogues are practically inert in this transformation.

3. Conclusion

In conclusion, we have investigated the selectivity of the intramolecular enyne metathesis catalyzed by representative first- and second-generation ruthenium carbenes [16]. This study witnesses the very subtle and cooperative influence of different parameters on the regiochemical course of this reaction. In the case of enynes containing an internal triple bond and *a monosubstituted double bond* only the application of first-generation catalysts leads selectively to the formation of the expected product **4**. If the substrate bears an internal triple bond and *a 1,1-disubstituted alkene fragment* first-generation catalysts are inert in this cyclization, while in the case of more reactive second-generation catalysts the transformation proceeds with high conversion, but is not selective. Only when a substrate contains a less accessible (e.g. sterically hindered) triple bond the application of second-generation catalysts can ensure a high level of selectivity.

4. Experimental

4.1. General procedure for enyne metathesis

A Schlenck flask was charged with 4-(allyloxy)-2-butynyl acetate (**3d**) (42 mg, 0.25 mmol) in CH_2Cl_2 (3 ml). To a stirred solution of substrate was successively added a solution of catalyst (**N1**) (4 mg, 0.006 mmol) in CH_2Cl_2 (1 ml) and the resulting mixture was stirred at ambient temperature until TLC showed complete conversion of the substrate (1 h). The solvent was evaporated in vacuum and the residue was purified by flash chromatography with cyclohexane/ethyl acetate (9/1) as the eluent, thus providing product **4d** as a colorless oil (39 mg, 94%).

4.2. Analysis data

N-Allyl-*N*-(2-butynyl)-4-methylbenzenesulfonamide (colorless oil) (**3a**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.74 (d, J = 8.4 Hz, 2H), 7.29 (d, J = 8.4 Hz, 2H), 5.82–5.63 (m, 1H), 5.32–5.15 (m, 2H), 4.05–3.97 (m, 2H), 3.79 (d, J = 6.4 Hz, 2H), 2.42 (s, 3H), 1.55–1.52 (m, 3H). Analytical data are in agreement with those published in literature [17].

3-Isopropenyl-1-[(4-methylphenyl)sulfonyl]-2,5-dihydro-1*H*-pyrrole (colorless crystals) (**4a**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.73 (dd, J = 6.4, 1.8 Hz, 2H), 7.31 (dd, J = 8.6, 0.6 Hz, 2H), 5.58 (s, 1H), 4.98 (s, 1H), 4.76 (s, 1H), 4.28–4.16 (m, 4H), 2.42 (s, 3H), 1.84 (s, 3H). Analytical data are in agreement with those published in literature [17].

4-Methyl-3-methylene-1-[(4-methylphenyl)sulfonyl]-1,2,3,6-tetrahydropyridine (**5a**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.65 (d, J = 8.4 Hz, 2H), 7.28 (d, J = 8.4 Hz, 2H), 5.52 (s, 1H), 4.92 (s, 1H), 4.65 (s, 1H), 3.81–3.76 (m, 2H), 3.69 (bs, 2H), 2.41 (s, 3H), 1.74–1.71 (m, 3H). GC–MS (*m*/*z*): 263 ($M^{\bullet+}$), 248, 199, 155, 139, 108, 107, 91, 81, 65, 53, 39. Values of NMR shifts were excluded from mixture of **4a** and **5a**.

1-Isopropenyl-3-[(4-methylphenyl)sulfonyl]-3-azabicyclo-[3.1.0]hexane (**6a**). GC–MS (*m*/*z*): 277 ($M^{\bullet+}$), 262, 248, 236, 222, 155, 139, 122, 106, 91, 79, 65, 55, 41.

Diethyl 2-allyl-2-(2-butynyl)malonate (colorless oil) (**3b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.72–5.51 (m, 1H), 5.19–5.00 (m, 2H), 4.17 (q, J = 7.2 Hz, 4H), 2.81–2.67 (m, 4H), 1.73 (t, J = 2.6 Hz, 3H), 1.22 (t, J = 7.2 Hz, 6H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 169.9, 132.0, 119.3, 78.7, 73.3, 61.4, 56.9, 36.4, 22.8, 14.0, 3.4. Analytical data are in agreement with those published in the literature [17].

Diethyl 3-isopropenyl-3-cyclopentene-1,1-dicarboxylate (colorless oil) (**4b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.58 (s, 1H), 4.91 (d, J = 6.2 Hz, 2H), 4.19 (q, J = 7.2 Hz, 4H), 3.17–3.11 (m, 4H), 1.89 (s, 3H), 1.24 (t, J = 7.2 Hz, 6H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 172.0, 141.4, 138.8, 123.7, 113.2, 61.5, 58.9, 41.0, 40.5, 20.4, 14.0. Analytical data are in agreement with those published in the literature [17].

Diethyl 4-methyl-5-methylene-3-cyclohexene-1,1-dicarboxylate (**5b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.56 (s, 1H), 4.97 (s, 1H), 4.76 (s, 1H), 4.18 (q, J = 7.2 Hz, 4H), 2.87 (s, 2H), 2.67 (s, 2H), 1.79 (bs, 3H), 1.20 (t, J = 7.2 Hz, 6H). GC–MS (*m*/*z*): 252 ($M^{\bullet+}$), 207, 179, 163, 151, 133, 119, 105, 91, 77, 65, 51. Values of NMR shifts were excluded from mixture of **4b** and **5b**.

Diethyl 1-isopropenylbicyclo[3.1.0]hexane-3,3-dicarboxylate (**6b**). GC–MS (*m*/*z*): 266 ($M^{\bullet+}$), 252, 221, 193, 177, 163, 147, 119, 105, 91, 79.

4-Isopropenyl-1-[(4-methylphenyl)sulfonyl]-1,2,3,6-tetrahydropyridine (white crystals) (**4c**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.71–7.65 (m, 2H), 7.34–7.27 (m, 2H), 5.69 (t, J = 3.6 Hz, 1H), 4.92 (d, J = 6.6 Hz, 2H), 3.69–3.67 (m, 2H), 3.19 (t, J = 5.6 Hz, 2H), 2.43–2.36 (m, 5H), 1.84 (s, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 143.5, 141.7, 135.2, 132.9, 129.6, 127.7, 118.9, 111.7, 45.2, 42.9, 25.7, 21.5, 20.2. IR (film) 3087, 2930, 2905, 2819, 1608, 1596, 1462, 1442, 1371, 1343, 1317, 1309, 1289, 1244, 1209, 1164, 1106, 1088, 953, 939, 909, 889, 819, 802, 734, 658, 622, 548 cm^{-1}. LSIMS (*m*/*z*)—$[M + Na]^+$ calcd for $C_{11}H_{18}O_2Na$: 205.1199; found: 205.1189. Anal calcd for $C_{15}H_{19}NO_2S$ C, 64.95; H, 6.90; N, 5.05; S, 11.56; found C, 64.86; H, 6.90; N, 5.14; S, 11.45.

4-Isopropenyl-1-[(4-methylphenyl)sulfonyl]-1,2,3,6-tetrahydropyridine (**5c**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.65–7.59 (m, 2H), 7.24–7.20 (m, 2H), 5.51 (t, J = 3.6 Hz, 1H), 4.83 (s, 1H), 4.61 (s, 1H), 3.90–3.87 (m, 2H), 3.40 (t, J = 5.6 Hz, 2H), 2.49–2.39 (m, 5H), 1.78 (s, 3H). GC–MS (*m*/*z*): 277 ($M^{\bullet+}$), 262, 236, 223, 155, 136, 122, 106, 95, 79, 67, 55, 41. Values of NMR shifts were excluded from mixture of **4c** and **5c**.

4-(Allyloxy)-2-butynyl acetate (colorless oil) (**3d**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.97–5.78 (m, 1H), 5.33–5.15 (m, 2H), 4.69 (t, J = 1.8 Hz, 2H), 4.16 (t, J = 1.8 Hz, 2H), 4.02 (dt, J = 5.6, 1.4 Hz, 2H), 2.07 (s, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 170.0, 133.7, 117.8, 82.7, 80.2, 70.6, 57.2, 52.2, 20.6. IR (film) 2944, 2856, 1749, 1648, 1438, 1379, 1357, 1225, 1137, 1086, 1028, 969, 928 cm^{-1}. LSIMS (*m*/*z*)—$[M + Na]^+$ calcd for $C_9H_{12}O_3Na$: 191.0679; found: 191.0681.

2-(2,5-Dihydro-3-furanyl)-2-propenyl acetate (colorless oil) (**4d**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.89 (s, 1H), 5.29 (s, 1H), 4.95 (s, 1H), 4.76 (bs, 6H), 2.10 (s, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 170.5, 136.7, 135.0, 122.7, 115.7, 76.4, 75.0, 64.8, 20.9. IR (film) 2942, 2876, 1740, 1435, 1375, 1232, 1165, 1030, 875 cm^{-1}. HRMS–EI (*m*/*z*)—$[M]^{\bullet+}$ calcd for $C_9H_{12}O_3$: 168.0786; found: 168.0779.

(3-Methylene-3,6-dihydro-2*H*-pyran-4-yl)methyl acetate (**5d**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.98 (s, 1H), 5.00 (bs, 1H), 4.87 (s, 1H), 4.81–4.78 (m, 2H), 4.29–4.26 (m, 2H), 4.24–4.22 (m, 2H), 2.07 (s, 3H). GC–MS (*m*/*z*): 168 ($M^{\bullet+}$), 108, 95, 79, 65, 53, 43, 39. Values of NMR shifts were excluded from mixture of **4d** and **5d**.

2-(3-Oxabicyclo[3.1.0]hex-1-yl)-2-propenyl acetate (**6d**). GC–MS (*m*/*z*): 182 ($M^{\bullet+}$), 168, 140, 122, 111, 94, 77, 66, 51, 43.

2-{[4-(Allyloxy)-2-butynyl]oxy}tetrahydro-2*H*-pyran (yellowish oil) (**3e**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 6.00–5.80 (m, 1H), 5.35–5.17 (m, 2H), 4.80 (t, J = 3.0 Hz, 1H), 4.33–4.28 (m, 2H), 4.20–4.18 (m, 2H), 4.05 (dt, J = 4.6, 1.6 Hz, 2H), 3.89–3.78 (m, 1H), 3.58–3.47 (m, 1H), 1.93–1.44 (m, 6H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 133.9, 117.8, 96.8, 82.3, 81.8, 70.6, 62.0, 57.5, 54.3, 30.2, 25.3, 19.0. IR (film) 3080, 2944, 2854, 1732, 1648, 1454, 1442, 1389, 1344, 1264, 1202, 1183, 1120, 1079, 1055, 1025, 971, 944, 930, 903, 871, 816 cm^{-1}. LSIMS (*m*/*z*)—$[M + Na]^+$ calcd for $C_{12}H_{18}O_3Na$: 233.1148; found: 233.1137.

2-(2,5-Dihydro-3-furanyl)-2-propenyl tetrahydro-2*H*-pyran-2-yl ether (colorless oil) (**4e**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.95 (s, 1H), 5.32 (s, 1H), 4.92 (s, 1H), 4.82–4.72 (m, 4H), 4.66 (t, J = 3.0 Hz, 1H), 4.48–4.42 (m, 1H), 4.19–4.12 (m, 1H), 3.93–3.82 (m, 1H), 3.58–3.49 (m, 1H), 1.93–1.46 (m, 6H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 137.0, 122.2, 114.5, 98.0, 76.4, 75.2, 67.8, 62.3, 30.6, 25.4, 19.5. IR (film) 3089, 2945, 2870, 1733, 1604, 1443, 1387, 1352, 1262, 1202, 1183, 1128, 1075, 1030, 977, 903, 870, 813 cm^{-1}. LSIMS (*m*/*z*): $[M + Na]^+$ 233.1.

(3-Methylene-3,6-dihydro-2*H*-pyran-4-yl)methyl tetrahydro-2*H*-pyran-2-yl ether (**5e**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 6.00 (s, 1H), 5.05 (s, 1H), 4.84 (s, 1H), 4.67 (t, J = 3.0 Hz, 1H), 4.47–4.41 (m, 1H), 4.32–4.26 (m, 2H), 4.25–4.22 (m, 2H), 4.16–4.10 (m, 1H), 3.93–3.82 (m, 1H), 3.58–3.49 (m, 1H), 1.93–1.46 (m, 6H). GC–MS (*m*/*z*): 210 ($M^{\bullet+}$), 192, 148, 126, 110, 108, 95, 85, 79, 67, 55, 41. Values of NMR shifts were excluded from mixture of **4e** and **5e**.

1-{1-[(Tetrahydro-2*H*-pyran-2-yloxy)methyl]vinyl}-3-oxabicyclo[3.1.0]hexane (**6e**). GC–MS (*m*/*z*): 224 ($M^{\bullet+}$), 207, 193, 151, 139, 122, 109, 91, 85, 79, 67, 55, 41.

[1-(Allyloxy)-1-phenyl-2-butynyl]benzene (colorless oil) (**3f**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.64–7.56 (m, 4H), 7.40–7.20 (m, 6H), 6.12–5.93 (m, 1H), 5.38 (dq, J = 17.4, 1.8 Hz 1H), 5.19 (dq, J = 10.4, 1.4 Hz, 1H), 4.06 (dq, J = 6.8, 1.6 Hz, 2H), 2.03 (s, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 144.1, 135.1, 128.0, 127.3, 126.6, 115.8, 85.7, 65.9, 65.6, 3.9. EI (*m*/*z*)—$[M]^+$ calcd for $C_{19}H_{18}O$: 262.1358; found: 262.1349.

3-Isopropenyl-2,2-diphenyl-2,5-dihydrofuran (colorless oil) (**4f**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.46–7.30 (m, 10H), 6.22 (s, 1H), 4.93 (s, 1H), 4.74 (s, 2H), 4.64 (s, 1H), 1.98 (s, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 145.6, 143.4, 136.6, 128.6, 127.6, 127.4, 126.6, 117.4, 94.8, 72.4, 22.9. IR (film) 3060, 2924,

1761, 1599, 1491, 1447, 1378, 1227, 1181, 1065, 1032, 932, 907, 759, 699. EI (*m/z*)—$[M]^+$ calcd for $C_{19}H_{18}O$: 262.1358; found: 262.1346.

1-Isopropenyl-2,2-diphenyl-3-oxabicyclo[3.1.0]hexane (**6f**). GC–MS (*m/z*): 276 ($M^{\bullet+}$), 261, 233, 215, 185, 105, 77, 66.

1-(Allyloxy)-4-[(2-methyl-2-propenyl)oxy]-2-butyne (colorless oil) (**7b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.99–5.80 (m, 1H), 5.35–5.16 (m, 2H), 4.98–4.89 (m, 2H), 4.20–4.15 (m, 4H), 4.05 (dt, $J = 4.2$, 1.4 Hz, 2H), 3.95 (bs, 2H), 1.73 (bs, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 141.3, 133.9, 117.7, 112.9, 82.4, 82.1, 73.6, 70.5, 57.3, 57.2, 19.5. IR (film) 3079, 2920, 2853, 1654, 1451, 1376, 1350, 1264, 1249, 1139, 1120, 1078, 992, 928, 903 cm^{-1}. LSIMS (*m/z*)—$[M + Na]^+$ calcd for $C_{11}H_{16}O_2Na$: 203.1043; found: 203.1046.

3-(1-{[(2-Methyl-2-propenyl)oxy]methyl}vinyl)-2,5-dihydrofuran (colorless oil) (**8b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.97–5.96 (m, 1H), 5.29–5.28 (m, 1H), 4.99–4.95 (m, 1H), 4.92–4.89 (m, 2H), 4.81–4.73 (m, 4H), 4.16–4.15 (m, 2H), 3.91–3.90 (m, 2H), 1.75–1.74 (m, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 142.0, 137.0, 122.4, 114.8, 112.4, 76.4, 75.1, 74.1, 71.0, 19.5. GC–MS (*m/z*): 180 ($M^{\bullet+}$), 165, 137, 124, 110, 79, 68, 41.

3-(2′,5′-Dihydro-3-methylfuranyl)-2,5-dihydrofuran (colorless oil) (**10b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.58 (s, 1H), 4.95–4.89 (m, 2H), 4.80–4.75 (m, 2H), 4.71–4.65 (m, 2H), 4.64–4.57 (m, 2H), 1.77 (bs, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 132.2, 132.0, 122.4, 80.7, 77.5, 75.2, 11.1. GC–MS (*m/z*): 152 ($M^{\bullet+}$), 137, 124, 109, 91, 81, 67, 39.

3-Methylene-4-{[(2-methyl-2-propenyl)oxy]methyl}-3,6-dihydro-2*H*-pyran (**11b**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.97 (s, 1H), 5.05 (s, 1H), 4.97–4.95 (m, 1H), 4.93–4.30 (m, 1H), 4.85 (s, 1H), 4.31–4.26 (m, 2H), 4.24–4.22 (m, 2H), 4.15–4.11 (m, 2H), 3.90 (s, 2H), 1.74 (m, 3H). GC–MS (*m/z*): 180 ($M^{\bullet+}$), 165, 152, 124, 110, 95, 79, 68, 55, 41.

2,5-Bis(allyloxy)-2,5-dimethyl-3-hexyne (colorless oil) (**7c**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 6.04–5.84 (m, 2H), 5.32 (q, $J = 1.8$ Hz, 1H), 5.23 (q, $J = 1.8$ Hz, 1H), 5.17–5.12 (m, 1H), 5.11 (q, $J = 1.2$ Hz, 1H), 4.07 (dt, $J = 5.6$, 1.4 Hz, 4H), 1.46 (bs, 12H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 135.4, 116.3, 86.1, 70.3, 65.4, 28.9. IR (film) 3081, 2985, 2931, 2857, 1647, 1466, 1423, 1378, 1362, 1263, 1189, 1161, 1127, 1065, 1029, 994, 919, 895 cm^{-1}. LSIMS (*m/z*)—$[M + Na]^+$ calcd for $C_{14}H_{22}O_2Na$: 245.1512; found: 245.1503.

2,2′-Tetramethyl-5,5′-dihydro-[3,3′]bifuranyl (white crystals) (**10c**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.77–5.76 (m, 2H), 4.64–4.62 (m, 4H), 1.43 (s, 12H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 138.8, 122.0, 88.5, 72.0, 27.2. Analytical data are in agreement with those published in literature [18].

2-(Allyloxy)-2,5-dimethyl-5-[(2-methyl-2-propenyl)oxy]-3-hexyne (colorless oil) (**7d**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 6.04–5.85 (m, 1H), 5.34–5.11 (m, 2H), 5.02–4.96 (m, 1H), 4.88–4.83 (m, 1H), 4.08 (dt, $J = 5.6$, 1.4 Hz, 2H), 3.97 (bs, 2H), 1.76 (s, 3H), 1.46 (s, 12H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 142.8, 135.4, 116.4, 111.6, 86.3, 86.0, 70.4, 70.3, 68.3, 65.4, 28.9, 19.7. IR (film) 3078, 2984, 2927, 2856, 1649, 1456, 1377, 1361, 1261, 1189, 1160, 1093, 1066, 1030, 919, 897 cm^{-1}. LSIMS (*m/z*): $[M + Na]^+$ calcd for $C_{11}H_{18}O_2Na$: 205.1199; found: 205.1189.

3-(2′-Dimethyl-5′-dihydrofuranyl)-2,4-trimethyl-5-dihydrofuran (colorless oil) (**10d**). ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.57 (t, $J = 1.7$ Hz, 1H), 4.63 (d, $J = 1.7$ Hz, 2H), 4.49 (d, $J = 1.1$ Hz, 2H), 1.64 (t, $J = 1.1$ Hz, 3H), 1.34 (s, 6H), 1.31 (s, 6H). GC–MS (*m/z*): 208 ($M^{\bullet+}$), 193, 135, 107, 91, 65, 43.

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References

[1] M. Mori (Ed.), Ene-Yne Metathesis, Wiley/VCH, Weinheim, 2003.
[2] C.S. Poulsen, R. Madsen, Synthesis (2003) 1.
[3] S.T. Diver, A.J. Giessert, Chem. Rev. 104 (2004) 1317.
[4] A. Deiters, S.F. Martin, Chem. Rev. 104 (2004) 2199.
[5] T.M. Trnka, R.H. Grubbs, Acc. Chem. Res. 34 (2001) 18.
[6] J.S. Kingsbury, J.P.A. Harrity, P.J. Bonitatebus Jr., A.H. Hoveyda, J. Am. Chem. Soc. 121 (1999) 791.
[7] K. Grela, S. Harutyunyan, A. Michrowska, Angew. Chem. Int. Ed. 41 (2002) 4038.
[8] (a) K. Grela, M. Kim, Eur. J. Org. Chem. (2003) 963;
(b) A. Michrowska, Ł. Gułajski, K. Grela, Chem. Commun. (2006) 841.
[9] A. Michrowska, R. Bujok, S. Harutyunyan, V. Sashuk, G. Dolgonos, K. Grela, J. Am. Chem. Soc. 126 (2004) 9318.
[10] (a) T. Kitamura, Y. Sato, M. Mori, Chem. Commun. (2001) 1258;
(b) T. Kitamura, Y. Sato, M. Mori, Adv. Synth. Catal. 344 (2002) 678;
(c) A. Kinoshita, M. Mori, Synlett (1994) 1020.
[11] During preparation of this manuscript another very interesting work on the mechanism of enyne metathesis has been published: G.C. Lloyd-Jones, R.G. Margue, J.G. de Vries, Angew. Chem. Int. Ed. 44 (2005) 7442.
[12] J.J. Lippstreu, B.F. Straub, J. Am. Chem. Soc. 127 (2005) 7444.
[13] It was suggested that in the case of first generation Hoveyda catalysts phosphine dissociation plays also some role in the catalytic cycle, and the catalytically active 14-electron species formed in situ, at least partly, remains attached to the 2-alkoxystyrene fragment: M. Zaja, S.J. Connon, A.M. Dunne, M. Rivard, N. Buschmann, J. Jiricek, S. Blechert, Tetrahedron 59 (2003) 6545.
[14] A.K. Chatterjee, T.L. Choi, D.P. Sanders, R.H. Grubbs, J. Am. Chem. Soc. 125 (2003) 11360.
[15] B.P. Peppers, S.T. Diver, J. Am. Chem. Soc. 126 (2004) 9524.
[16] For some previous examples where different Ru catalysts give qualitatively different results in metathesis reactions, see;
(a) B. Trillo, M. Gulias, F. Lopez, L. Castedo, J.L. Mascarenas, J. Organomet. Chem. 690 (2005) 5609;
(b) D.J. Wallace, Tetrahedron Lett. 46 (2005) 591;
(c) V. Bhrsch, J. Neidhfer, S. Blechert, Angew. Chem. 118 (2006) 1324;
(d) See also F. Lopez, A. Delgado, J.R. Rodriguez, L. Castedo, J.L. Mascarenas, J. Am. Chem. Soc. 126 (2004) 10262.
[17] A. Fürstner, L. Ackermann, B. Gabor, R. Goddard, C.W. Lehmann, R. Mynott, F. Stelzer, O.R. Thiel, Chem. Eur. J. 7 (2001) 3236.
[18] A. Fürstner, L. Ackermann, K. Beck, H. Hori, D. Koch, K. Langemann, M. Liebl, C. Six, W. Leitner, J. Am. Chem. Soc. 123 (2001) 9000.