CHEMISTRY
A EUROPEAN JOURNAL

ChemPubSoc Europe

DOI: 10.1002/chem.201200188

Ruthenium-Catalyzed Functionalization of Pyrroles and Indoles with Propargyl Alcohols

Nora Thies, Cristian G. Hrib, and Edgar Haak*[a]

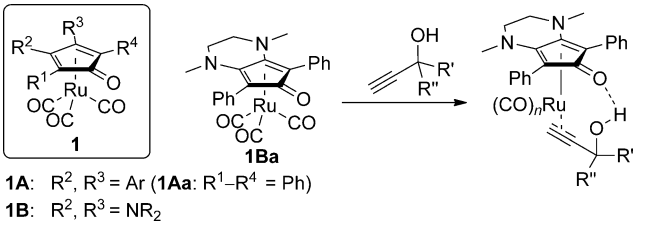
Abstract: Several ruthenium-catalyzed atom-economic transformations of propargyl alcohols with pyrroles or indoles leading to alkylated, propargylated, or annulated heteroaromatics are reported. The mechanistically distinct reactions are catalyzed by a single ruthenium(0) complex containing a redox-coupled dienone ligand. The mode of activation regarding the propargyl alcohols determines the reaction pathway and depends on the alcohols' substitution pattern. Secondary substrates form alkenyl complexes by a 1,2-hydrogen shift, whereas the transformation of tertiary substrates involves allenylidene intermediates. 1-Vinyl propargyl alcohols are converted by a cascade allylation/cyclization sequence. The environmentally benign processes are of broad scope and allow the selective synthesis of highly functionalized pyrroles and indoles generating water as the only waste product.

Keywords: atom economy · cooperative effects · heterocycles · homogeneous catalysis · ruthenium

Introduction

Ruthenium-catalyzed reactions of unsaturated substrates offer various atom-economic transformations. Nucleophilic additions through vinylidene or allenylidene complexes and redox isomerizations of allyl and propargyl alcohols have been described in particular besides metathesis and C–C-coupling reactions.[1] An interesting route to important alkaloid classes could be obtained by selective catalytic functionalization of pyrroles or indoles with propargyl alcohols. Trost and co-workers have reported a ruthenium-catalyzed formation of β-heteroarylated ketones from internal secondary propargyl alcohols by a redox isomerization process.[2a] A similar transformation catalyzed by phosphane-bridged diruthenium complexes was described by Nishibayashi and co-workers.[2b] The same group has demonstrated catalytic propargylations of various heteroaromatics with terminal secondary propargyl alcohols several times. These reactions are catalyzed by thiolate-bridged diruthenium complexes and proceed via allenylidene intermediates.[2c–f] The scope of alternative propargylations of heteroaromatics with propargyl alcohols catalyzed by Lewis acids,[3a–i] Brønsted acids,[3j] or iodine[3k] is largely restricted to internal aromatic substrates regarding the propargyl component. Few exceptions are observed when using *p*TsOH (*p*Ts = *para*-tosyl) as the catalyst.[3j]

In previous studies, we have shown that ruthenium complexes of redox-active cyclopentadienone (CPD) ligands (**1**) catalyze various transformations of propargyl alcohols.[4a–d] The catalytic activity of 3,4-diaryl-substituted complexes of the type **1A** is largely limited to the conversion of secondary propargyl alcohols,[4a,b] whereas in the presence of 3,4-diamino-substituted catalysts of the type **1B** primarily terminal secondary and tertiary propargyl alcohols are activated (Scheme 1).[4b–d] Secondary substrates can be converted into



1A: R^2, R^3 = Ar (**1Aa**: R^1–R^4 = Ph)
1B: R^2, R^3 = NR_2

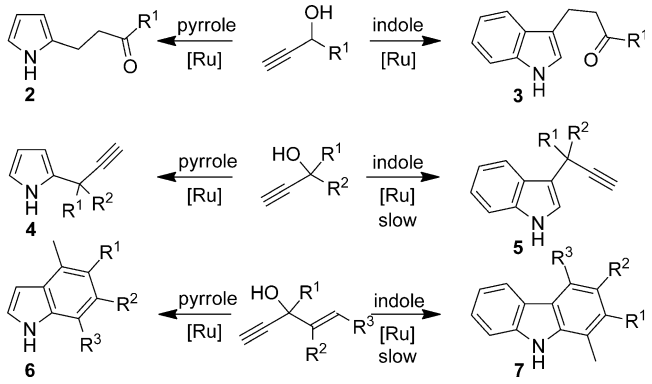
Scheme 1. Cyclopentadienone ruthenium complexes and substrate coordination.

enones, β-amino ketones, or enamino ketones[4a,b] by a redox isomerization process.[4b,5] Terminal propargyl alcohols allow the formation of α,β-unsaturated imines, allenyl carbamates, hydroxy enolesters, 4*H*-pyranes, or conjugated enynes via vinylidene or allenylidene intermediates.[4b–d] The chelating substrate coordination involving the basic coordination site of the electronically coupled ligand is crucial for these regioselective transformations (Scheme 1). Substrates without suitable hydrogen-bond donors are usually not converted.

Herein, we report several mechanistically different selective reactions of propargyl alcohols with pyrroles or indoles that are catalyzed by complex **1Ba**. These environmentally benign and atom-economic transformations proceed through

[a] N. Thies, Dr. C. G. Hrib, Prof. Dr. E. Haak
Institut für Chemie, Otto-von-Guericke-Universität Magdeburg
Universitätsplatz 2, 39106 Magdeburg (Germany)
E-mail: edgar.haak@ovgu.de

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201200188. It contains full characterization data of all reported products.



Scheme 2. Ruthenium-catalyzed transformations of propargyl alcohols with pyrrole or indole.

strikingly different reaction pathways that are determined by the nature of the propargyl substrates. By using pyrrole as the nucleophile, secondary propargyl alcohols form pyrrolyl propanones (**2**, Scheme 2) in the presence of catalyst **1Ba** and an acidic additive, whereas tertiary propargyl alcohols lead to propargylation of the pyrrole. 1-Vinyl propargyl alcohols that are easily accessible from enones are transformed to yield 4-methyl indoles (**6**, Scheme 2). By using indole as the nucleophile, the conversion of secondary propargyl alcohols leading to indolyl propanones (**3**) proceeds in high yields, whereas the transformations of tertiary propargyl alcohols to propargyl indoles (**5**) or of 1-vinyl propargyl alcohols to 1-methyl carbazoles (**7**) proceed slowly (Scheme 2). The corresponding alkyl or silyl propargyl ether or propargyl acetates are not converted under the reaction conditions. Ruthenium complexes of type **1A**, $[Ru_3(CO)_{12}]$, or $[RuCl_2(PPh_3)_3]$ offer no comparable catalytic activity. No transformation is observed in the absence of the catalyst or co-catalyst with the exception of strongly activated aromatic propargyl alcohols that may form elimination or substitution products under weakly acidic conditions.

Results and Discussion

X-ray single-crystal structure of catalyst 1Ba: We have previously reported the synthesis and catalytic activities of several complexes of the series **1A** and **1B** including **1Ba**.[4b,c] Its proposed structure is now confirmed by X-ray crystallography.[6] An image of the molecule is shown in Figure 1. The coordination environment of the ruthenium atom is comprised of three terminally coordinated carbonyl ligands and a η^4-CPD ligand (CPD = cyclopentadienone). The CPD–ruthenium bond lengths (average, 2.263 Å) contrast with the non-bonding interaction of the CPD carbonyl carbon atom with the metal (2.477 Å). Intra-ring distances involving metal-bonded carbon atoms range from 1.432 to 1.454 Å, in contrast with intra-ring distances involving C1 (1.498, 1.486 Å). The structural data indicates no bond alternation in the diene system but a longer bond between C2 and C3 (1.454 Å) with the closest metal coordination at C2

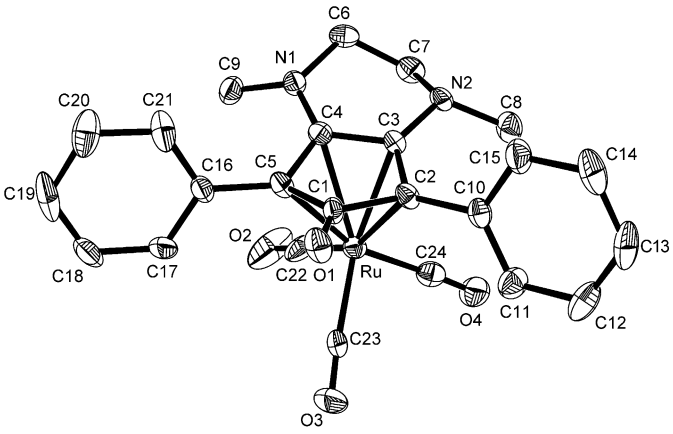
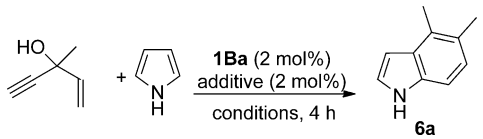


Figure 1. X-ray structure of **1Ba**[6] with thermal displacement parameters drawn at 50% probability. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å]: Ru–C1 2.477(3), Ru–C2 2.214(3), Ru–C3 2.264(5), Ru–C4 2.344(5), Ru–C5 2.229(5), Ru–C22 1.906(5), Ru–C23 1.965(6), Ru–C24 1.904(5), C1–C2 1.498(6), C2–C3 1.454(6), C3–C4 1.432(6), C4–C5 1.433(6), C5–C1 1.486(6), C1–O1 1.230(5), C2–C10 1.480(6), C3–N2 1.388(6), C4–N1 1.361(5), C5–C16 1.476(7), C22–O2 1.156(6), C23–O3 1.121(6), C24–O4 1.147(6).

(2.214 Å) and the largest metal–diene separation at C4 (2.344 Å). The ring carbonyl is twisted from the 1,4-diene plane, *exo* with respect to the metal and eclipses one of the terminally coordinated carbonyl ligands. This conformation leads to the lengthening of the Ru–C23 bond (1.965 Å) with concomitant shortening of the C23–O3 bond (1.121 Å). The tetrahydropyrazine system is almost planar with C7 twisted from the plane, *endo* with respect to the metal. The nitrogen atoms are not equivalent. N1 is more planarized and bound closer to the diene system (1.361 vs. 1.388 Å). This conformation reflects the asymmetric coordination of the metal, closer to C2 than to C5.

Catalytic transformation of 3-methyl-1-pentene-4-yn-3-ol with pyrrole by using complex 1Ba as the catalyst: Since catalysts of type **1** develop various activities towards unsaturated alcohols, we decided to investigate their interaction with 1-vinyl propargyl alcohols. These substrates can be regarded as allylic or as propargylic systems. Surprisingly 3-methyl-1-pentene-4-yn-3-ol reacts with pyrrole in the presence of catalyst **1Ba** and an acidic co-catalyst to yield 4,5-dimethyl-1*H*-indole (**6a**) as the sole product (Scheme 3). Re-



Scheme 3. Optimization of the reaction conditions.

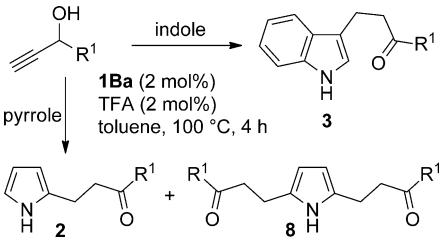
garding the co-catalyst several acidic additives are suitable. The best result for the conversion of 3-methyl-1-pentene-4-yn-3-ol with pyrrole is observed by using catalytic amounts

Table 1. Variation of additives and reaction conditions (CSA = camphor sulfonic acid, OTf = triflate).

Entry	Additive	Reaction conditions	Yield **6a** [%]
1	TFA	toluene, 100 °C	96
2	TFA	toluene, 60 °C	20
3	TFA	toluene, 25 °C	<1
4	TFA	THF, 65 °C	<1
5	TFA	$(CH_2Cl)_2$, 80 °C	<1
6	acetic acid	toluene, 100 °C	12
7	oxalic acid	toluene, 100 °C	82
8	cinnamic acid	toluene, 100 °C	58
9	CSA	toluene, 100 °C	32
10	*p*TsOH	toluene, 100 °C	27
11	$HBF_4{\cdot}Et_2O$	toluene, 100 °C	65
12	$BF_3{\cdot}Et_2O$	toluene, 100 °C	73
13	$In(OTf)_3$	toluene, 100 °C	<1
14	$Sc(OTf)_3$	toluene, 100 °C	<1
15	$Yb(OTf)_3$	toluene, 100 °C	<1

of trifluoroacetic acid (TFA) and **1Ba** in toluene at 100 °C (Scheme 3, Table 1). The discovery of this unique transformation led us to systematically investigate reactions of various propargyl alcohols with pyrroles or indoles by using complex **1Ba** as the catalyst.

Catalytic transformations of secondary propargyl alcohols: Pyrrolyl or indolyl propanones (**2** or **3**) are accessible from aliphatic or aromatic saturated or unsaturated terminal secondary substrates (Scheme 4, Table 2). Depending on the



Scheme 4. Transformation of secondary propargyl alcohols.

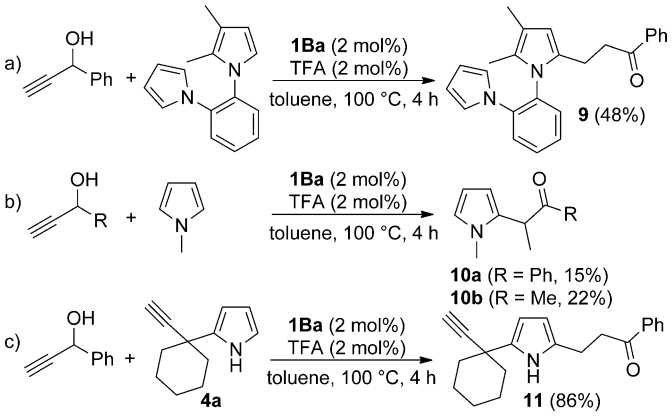
Table 2. Ruthenium-catalyzed functionalization of pyrrole or indole with secondary propargyl alcohols.

Entry	Nucleophile	R^1	Yield **2**/**3** [%]	Yield **8** [%][a]
1	pyrrole	Ph	<1	92 (**8a**)
2	pyrrole	Me	30 (**2b**)	65 (**8b**)
3	pyrrole	CH=CHPh	75 (**2c**)	<1
4	pyrrole	CH=CHMe	12 (**2d**)	18 (**8d**)
5	pyrrole	$CH{=}CH_2$	<1	<1
6	indole	Ph	80 (**3a**)	–
7	indole	Me	65 (**3b**)	–
8	indole	CH=CHPh	91 (**3c**)	–

[a] Yield based on the propargyl alcohol.

propargyl alcohol, the reaction leads to mono- or disubstitution. Internal secondary substrates like 1-phenylbut-2-yn-1-ol or pent-3-yn-2-ol are not converted.

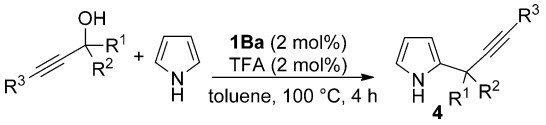
If different substituted pyrrole units are present, the one with higher electron density is selectively alkylated



Scheme 5. Transformation of substituted pyrroles.

(Scheme 5a). A few N-substituted pyrroles form isomeric products that are accompanied by several byproducts (Scheme 5b), whereas C-substituted pyrroles are very suitable substrates. Terminal alkyne motifs are tolerated under the reaction conditions (Scheme 5c).

Catalytic transformations of tertiary propargyl alcohols: Terminal tertiary propargyl alcohols lead to propargylation of the nucleophile (Scheme 6, Table 3). The conversion of aro-



Scheme 6. Transformation of tertiary propargyl alcohols.

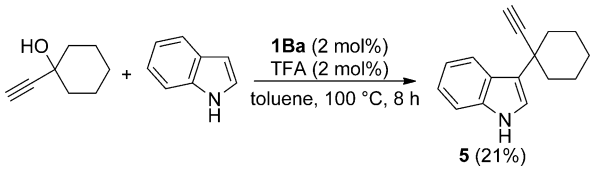
Table 3. Ruthenium-catalyzed propargylation of pyrrole.

Entry	R^1	R^2	R^3	Yield **4** [%]
1	Me	Et	H	91 (**4a**)
2	Me	$(CH_2)_2CH{=}CH_2$	H	69 (**4b**)
3	$-(CH_2)_5-$		H	72 (**4c**)
4	$-(CH_2)_5-$		Me	<1
5	$-(CH_2)_4-$		H	26 (**4e**)
6	Me	Ph	H	8 (**4f**)
7[a]	Me	Ph	Me	78 (**4g**)

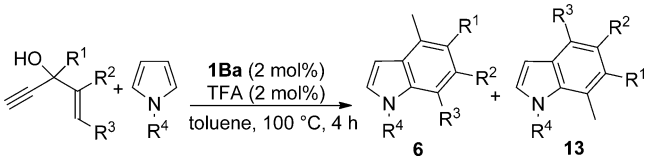
[a] Byproduct $PhC(CH_2)C_2Me$ (12%); product formation is independent from the ruthenium catalyst.

matic members occurs slowly (Table 3, entry 6). Internal aliphatic substrates are not reactive (Table 3, entry 4), whereas internal aromatic members form substitution or elimination products already in the presence of the acidic additive (Table 3, entry 7). Indole is slowly propargylated at the 3-position (Scheme 7).

Catalytic transformations of terminal tertiary 1-vinyl propargyl alcohols: The transformation of terminal tertiary 1-vinyl propargyl alcohols with pyrrole leads to 4-methyl indoles (**6**) in moderate to high yields (Scheme 8, Table 4).



Scheme 7. Ruthenium-catalyzed propargylation of indole.



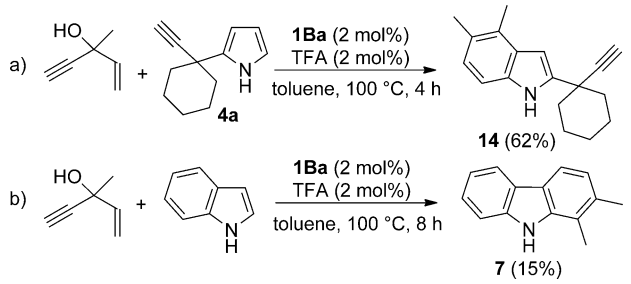
Scheme 8. Transformation of terminal 1-vinyl propargyl alcohols.

Table 4. Ruthenium-catalyzed indole formation.

Entry	R^1	R^2	R^3	R^4	Yield **6** [%]	Yield **13** [%]
1	Me	H	H	H	96 (**6a**)	<1
2	Me	H	Ph	H	58 (**6b**)	<1
3	Me	$-(CH_2)_4-$		H	35 (**6c**)	<1
4	Me	$-(CH_2)_3-$		H	44 (**6d**)	<1
5	Et	H	Me	H	60 (**6e**)	<1
6	Me	H	H	Me	45 (**6f**)	<1
7	Me	H	Ph	Me	68 (**6g**)	21 (**13g**)
8	Et	H	Me	Me	16 (**6h**)	5 (**13h**)
9	Me	H	H	Ph	<1	<1

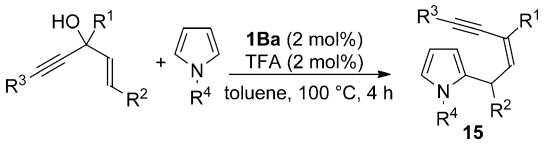
With *N*-methyl pyrrole, the regioisomeric 7-methylpyrroles (**13**) are formed as byproducts in some cases (Table 4, entries 7 and 8). The electron-poor *N*-phenyl pyrrole remains unreactive (Table 4, entry 9).

C-substituted pyrroles react comparatively fast (Scheme 9a), whereas the conversion of indole to the corresponding carbazole occurs slowly (Scheme 9b).



Scheme 9. Ruthenium-catalyzed formation of substituted indoles or carbazoles from 1-vinyl propargyl alcohols.

Catalytic transformations of internal 1-vinyl propargyl alcohols: Internal tertiary substrates lead to allylation of the nucleophile, yielding (*Z*)-enynes (Scheme 10, Table 5). Secondary internal substrates are not transformed with the exception of strongly activated members that yield the corresponding (*E*)-enynes (Table 5, entries 6–10).

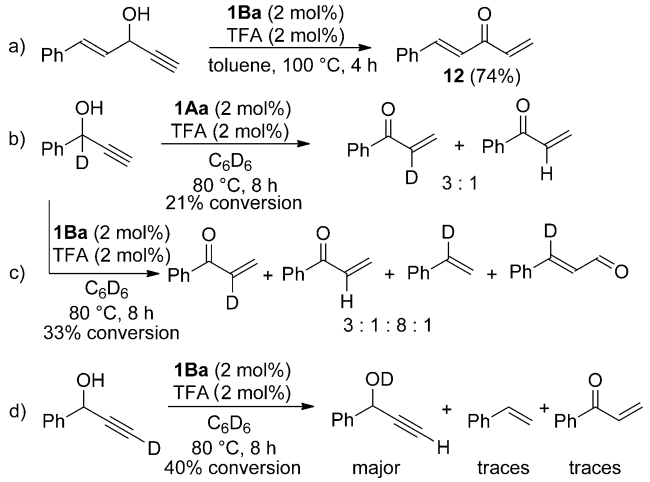


Scheme 10. Transformation of internal 1-vinyl propargyl alcohols.

Table 5. Ruthenium-catalyzed allylation.

Entry	R^1	R^2	R^3	R^4	Yield **15** [%]
1	Me	Ph	Ph	H	81 ((*Z*)-**15a**)
2	Me	Ph	Me	H	51 ((*Z*)-**15b**)
3	Me	Ph	Hex	H	97 ((*Z*)-**15c**)
4	Me	Ph	TMS	H	77 ((*Z*)-**15d**)
5	Me	Ph	Ph	Me	60 ((*Z*)-**15e**)
6	H	H	Ph	H	<1
7	H	H	Me	H	<1
8	H	Me	Me	H	<1
9	H	Ph	Me	H	<1
10	H	Ph	Ph	H	25 ((*E*)-**15j**)

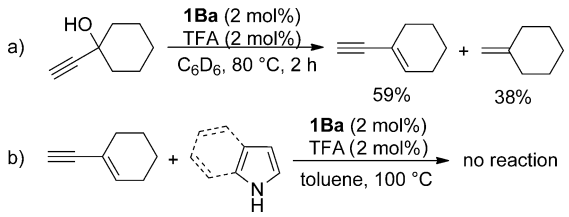
Mechanistic studies: The conversion of secondary propargyl alcohols is initiated by a redox isomerisation process. This leads to the formation of conjugated enones in the absence of a suitable nucleophile (Scheme 11a). Complexes of type



Scheme 11. Transformation of secondary propargyl alcohols in the absence of a suitable nucleophile.

1A are known to activate only secondary propargyl alcohols by a 1,2-hydrogen shift (Scheme 11b).[4b,5] In contrast, the similar transformation catalyzed by complexes of type **1B** also leads to CO-shortened alkenes and Meyer–Schuster products (Scheme 11c). The two additional compounds may be formed from an allenylidene species.[1,4b,7a] C3-deuterated substrates yield only traces of the former products aside from the H/D-exchanged compound as the major product (Scheme 11d). These results indicate an initial activation of the terminal C–H bond.

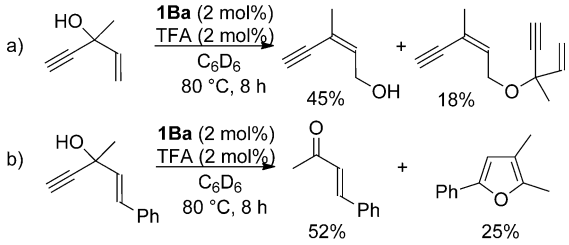
Terminal tertiary propargyl alcohols are converted into mixtures of conjugated enynes and CO-shortened alkenes in



Scheme 12. Transformation of tertiary propargyl alcohols in the absence of a suitable nucleophile and exclusion of a potential reaction pathway.

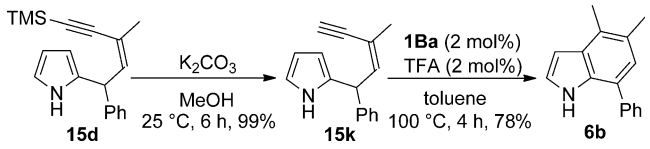
the absence of a suitable nucleophile (Scheme 12a). Both products may be derived from an allenylidene intermediate.[1,4b,7a–c] A subsequent ruthenium-catalyzed transformation of the conjugated enyne with pyrrole or indole does not occur (Scheme 12b). A potential reaction pathway via the initial formation of an enyne can therefore be excluded.

Tertiary 1-vinyl propargyl alcohols undergo a formal allylic rearrangement in the absence of a suitable nucleophile. The rearranged alcohol may cyclise to form the corresponding furan. A competing elimination of acetylene is observed in the case of aromatic substrates (Scheme 13).



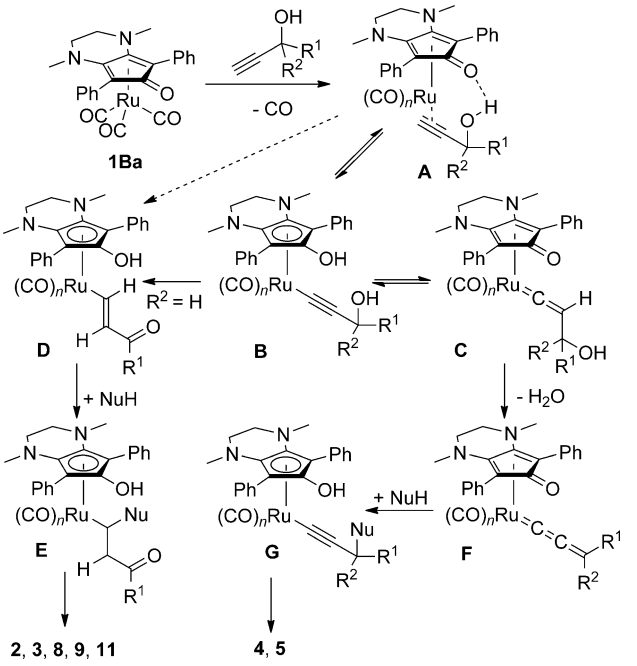
Scheme 13. Transformation of 1-vinyl propargyl alcohols in the absence of a suitable nucleophile.

The cyclization of the terminal enyne **15k**, formed from the allylated product **15d** by deprotection, also occurs by ruthenium catalysis. No transformation of **15k** is observed in the absence of the catalyst or co-catalyst (Scheme 14).



Scheme 14. Ruthenium-catalyzed enyne cyclization.

Overall mechanism: We assume that the initially formed π-complex **A** is in equilibrium with alkynyl complex **B** and vinylidene species **C**. Similar equilibria have been reported previously.[1,7c] Complexes of type **1A** transform terminal and internal π-complexed secondary propargyl alcohols directly by a 1,2-hydrogen shift.[4b,5] The analogous transformation catalyzed by complexes of type **1B** is limited to terminal substrates and may depend on the initial formation of alkynyl species **B**. The latter should allow the intramolecular protonation of the triple bond. Although the results of our mechanistic studies support this mechanism, a direct conversion of the π-complexed substrate cannot be excluded at this time. Nucleophilic attack on the resulting *trans*-alkenyl complex **D** leads to compound **E** that reductively eliminates the product under regeneration of the active catalytic species. By using terminal tertiary substrates, the corresponding vinylidene complex **C** may easily form allenylidene species **F**. Nucleophilic attack leads to alkynyl complex **G**, which eliminates the substitution product reductively (Scheme 15).

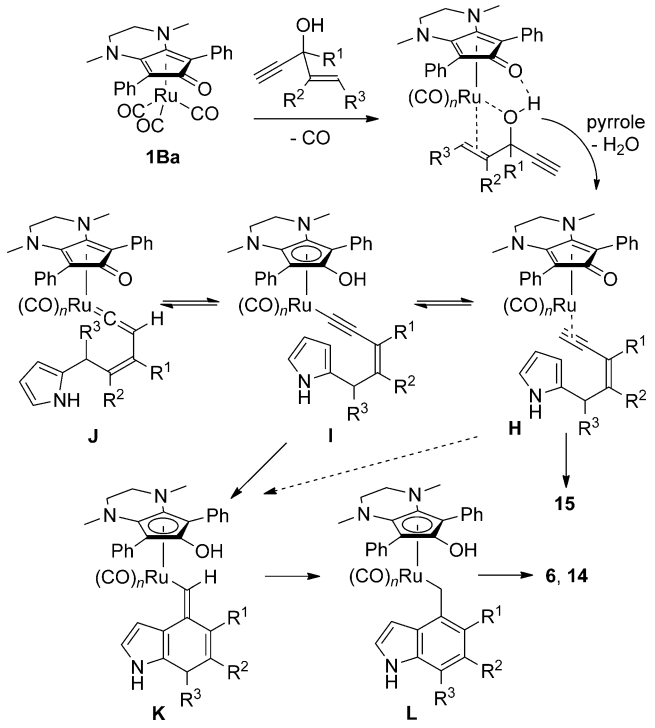


Scheme 15. Proposed mechanisms regarding the catalytic conversion of secondary and tertiary substrates.

1-Vinyl propargyl alcohols lead to the allylation of the nucleophile yielding the sterically less hindered (*Z*)-enynes in the case of tertiary substrates. A closely related ruthenium-catalyzed transformation of allylic alcohols has been reported previously.[7d,e] Internal substrates are not further converted. In the case of terminal substrates, the resulting π-complex **H** is in equilibrium with alkynyl species **I** and vinylidene complex **J** (Scheme 16).[1,7c] The following cyclization leads to alkenyl complex **K** and that may be formed from π-complex **H** or alkynyl species **I**. We believe the latter, since no cyclization occurs with internal substrates. A 1,5-hydrogen shift followed by reductive elimination of the product regenerates the active catalytic species (Scheme 16).

Conclusion

We have presented a selective and atom-economic functionalization of pyrroles or indoles with terminal propargyl alco-



Scheme 16. Proposed mechanisms regarding the catalytic transformations of 1-vinyl propargyl alcohols.

hols catalyzed by ruthenium complex **1Ba**. The reaction pathway depends on the alcohols' substitution pattern. Three fundamentally different modes of activation can be distinguished. Secondary substrates form alkenyl complexes by a 1,2-hydrogen shift, whereas the transformation of tertiary substrates involves allenylidene intermediates. The overall reactions lead to the formation of β-heteroarylated ketones in the former and to propargylated heteroaromatics in the latter case. 1-Vinyl propargyl alcohols are converted by a cascade allylation/cyclization sequence to yield cycloaddition products in the presence of the binucleophilic pyrroles or indoles. The stepwise combination of these transformations allows the selective synthesis of highly functionalized pyrroles and indoles by using a single pre-catalyst and generating water as the only waste product. Further investigations regarding the reaction mechanisms, scope, and limitations focused on sequential catalyzed processes and asymmetric catalytic applications by the use of axial-chiral members of the series of complexes **1B** are currently under investigation.

Experimental Section

General methods: All reactions were carried out in a dry atmosphere under argon by using standard Schlenck techniques. The chemicals used were dried and purified according to common procedures. Products were identified by spectroscopic analysis (^{1}H NMR, ^{13}C NMR, IR, MS, HRMS). IR spectra were obtained on a Perkin–Elmer FTIR 2000. NMR spectra were recorded on a BRUKER DPX 400 or a BRUKER AVANCE 600 spectrometer. MS and HRMS data were obtained on a FINNIGAN MAT 91. The intensity data of **1Ba** were collected on a STOE & CIE IPDS 2T diffractometer with $Mo_{K\alpha}$ radiation. The data were collected with the STOE & CIE X-AREA[8a] program by using ω-scans. The space group was determined with the X-RED32[8a] program. The structure was solved by direct methods (SHELXS-97)[8b] and refined by full-matrix least-squares methods on F^2 by using SHELXL-97.[8c] Catalysts **1Aa** and **1Ba** (except for the crystal structure) have previously been published.[4b] CCDC-853116 (**1Ba**)[6] contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

General catalytic procedure: Catalyst **1Ba** (0.02 mmol) was dissolved in toluene (1 mL) and TFA diluted in toluene (0.02 mmol, 1 M), the propargyl alcohol (1 mmol) and the pyrrole (1 mmol) or indole (1 mmol) were subsequently added. The mixture was stirred at 100 °C for 4 or 8 h under argon. Evaporation of the solvent and flash column chromatography on silica furnished the purified products.

Data of selected compounds

Compound ***2c*** *($C_{15}H_{15}NO$)*: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.03$ (t, $J = 7.0$ Hz, 2H), 3.06 (t, $J = 7.0$ Hz, 2H), 5.91 (brs, 1H), 6.32 (brs, 1H), 6.76 (brs, 1H), 6.80 (d, $J = 16.0$ Hz, 1H), 7.27–7.59 (m, 5H), 7.64 (d, $J = 16.0$ Hz, 1H), 8.80 ppm (brs; N–H); ^{13}C NMR (100 MHz, DEPT, $CDCl_3$): $\delta = 21.7$ (CH_2), 40.9 (CH_2), 104.7 (CH), 107.7 (CH), 117.5 (CH), 125.8 (CH), 128.1 (CH), 128.7 (CH), 130.2 (CH), 130.3 (C), 134.1 (C), 142.6 (CH), 200.1 ppm (C); IR: $\tilde{\nu} = 3346$ (m), 3057 (m), 3025 (m), 2922 (m), 2040 (w), 1965 (w), 1686 (s), 1655 (s), 1608 (s), 1575 (s), 1494 (s), 1449 (s), 1337 (s), 1178 (s), 1096 (s), 974 (s), 750 (s), 697 cm^{-1} (s); MS (EI): m/z (%): 225 [M^+] (22), 149 (39), 131 (100), 105 (57), 103 (80), 93 (30), 91 (31), 77 (80); HRMS: m/z calcd for $C_{15}H_{15}NO$: 225.1154 [M^+]; found: 225.1151.

Compound ***3c****[9a] ($C_{19}H_{17}NO$)*: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 3.13$ (t, $J = 6.8$ Hz, 2H), 3.23 (t, $J = 6.8$ Hz, 2H), 6.78 (d, $J = 16.4$ Hz, 1H), 6.99 (brs, 1H), 7.19–7.51 (m, 8H), 7.57 (d, $J = 16.4$ Hz, 1H), 7.70 (d, $J = 7.6$ Hz, 1H), 8.16 ppm (brs; N–H); ^{13}C NMR (100 MHz, DEPT, $CDCl_3$): $\delta = 19.8$ (CH_2), 41.2 (CH_2), 111.2 (CH), 115.0 (C), 118.6 (CH), 119.1 (CH), 121.6 (CH), 121.8 (CH), 126.2 (CH), 127.1 (C), 128.2 (CH), 128.8 (CH), 130.4 (CH), 134.3 (C), 136.3 (C), 142.6 (CH), 200.3 ppm (C); IR: $\tilde{\nu} = 3400$ (s), 3055 (m), 3024 (m), 2924 (m), 2070 (w), 2006 (w), 1958 (w), 1686 (s), 1655 (s), 1607 (s), 1576 (s), 1493 (m), 1457 (s), 1413 (m), 1338 (m), 1180 (s), 1095 (w), 977 (m), 742 (s), 700 (m), 690 cm^{-1} (m); MS (EI): m/z (%): 275 [M^+] (100), 257 (75), 144 (98), 130 (86), 105 (38), 103 (37), 77 (40), 61 (39), 60 (48); HRMS: m/z calcd for $C_{19}H_{17}NO$: 275.1310 [M^+]; found: 275.1310.

Compound ***4a*** *($C_{12}H_{15}N$)*: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.60$ (s, 3H), 1.80–1.85 (m, 2H), 1.99–2.05 (m, 2H), 2.40 (s, 1H), 4.94 (dd, $J = 10.4$, 1.2 Hz, 1H), 5.01 (dd, $J = 16.8$, 1.2 Hz, 1H), 5.80 (ddt, $J = 16.8$, 10.4, 6.4 Hz, 1H), 6.01 (brs, 1H), 6.19 (brs, 1H), 6.69 (brs, 1H), 8.46 ppm (brs; N–H); ^{13}C NMR (100 MHz, DEPT, $CDCl_3$): $\delta = 29.3$ (CH_3), 29.8 (CH_2), 35.8 (C), 43.0 (CH_2), 71.0 (CH), 87.9 (C), 102.9 (CH), 108.7 (CH), 114.4 (CH_2), 115.8 (CH), 135.0 (C), 138.2 ppm (CH); IR: $\tilde{\nu} = 3420$ (m), 3304 (s), 2950 (s), 2868 (s), 2104 (w), 1694 (s), 1466 (s), 1098 (w), 1039 (m), 990 (m), 922 (m), 787 (m), 720 cm^{-1} (s); MS (EI): m/z (%): 173 [M^+] (58), 158 (15), 130 (100), 117 (39); HRMS: m/z calcd for $C_{12}H_{15}N$: 173.1204 [M^+]; found: 173.1204.

Compound ***6a****[9b] ($C_{10}H_{11}N$)*: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 2.47$ (s, 3H), 2.58 (s, 3H), 6.63 (brs, 1H), 7.11 (d, $J = 8.4$ Hz, 1H), 7.16 (brs, 1H), 7.18 (d, $J = 8.4$ Hz, 1H), 8.05 ppm (brs; N–H); ^{13}C NMR (100 MHz, DEPT, $CDCl_3$): $\delta = 15.4$ (CH_3), 19.2 (CH_3), 100.7 (CH), 108.1 (CH), 123.7 (CH), 124.5 (CH), 125.3 (C), 127.4 (C), 128.4 (C), 134.1 ppm (C); IR: $\tilde{\nu} = 3392$ (s), 2922 (s), 2856 (s), 2274 (w), 1991 (w), 1656 (s), 1485 (s), 1451 (s), 1328 (s), 1240 (s), 1153 (s), 1091 (s), 873 (w), 802 (m), 768 (s), 725 (s), 606 (w), 555 (w), 521 cm^{-1} (w); MS (EI): m/z (%): 145 [M^+] (100), 144 (78), 130 (95); HRMS: calcd for $C_{10}H_{11}N$: 145.0891 [M^+]; found: 145.0891.

Compound ***15c*** *($C_{22}H_{27}N$)*: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 0.80$–0.83 (m, 3H), 1.18–1.24 (m, 4H), 1.32–1.39 (m, 2H), 1.44–1.52 (m, 2H), 1.80 (s, 3H), 2.29 (t, $J = 7.0$ Hz, 2H), 5.16 (d, $J = 9.8$ Hz, 1H), 5.76 (brs, 1H), 5.88 (d, $J = 9.9$ Hz, 1H), 6.05 (dd, $J = 5.7$, 2.9 Hz, 1H), 6.61 (brs, 1H),

7.09–7.24 (m, 5H), 7.86 ppm (brs; N–H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.0 (CH_3), 19.5 (CH_2), 22.6 (CH_2), 23.5 (CH_3), 28.6 (CH_2), 28.8 (CH_2), 31.4 (CH_2), 45.8 (CH), 79.6 (C), 94.7 (C), 105.9 (CH), 108.2 (CH), 116.9 (CH), 119.4 (C), 126.7 (CH), 128.2 (CH), 128.6 (CH), 133.8 (C), 136.3 (CH), 142.4 ppm (C); NOESY (600 MHz, $CDCl_3$): cross-peak: 1.80/5.88, *Z* isomer; IR $\tilde{\nu}$ = 3432 (m), 3027 (m), 2955 (s), 2928 (s), 2857 (s), 2212 (w), 1946 (w), 1709 (m), 1493 (m), 1453 (m), 1377 (m), 1355 (m), 1029 (m), 968 (w), 909 (m), 885 (w), 733 (s), 700 (s), 648 cm^{-1} (w); MS (EI): *m*/*z* (%): 305 [M^+] (50), 290 (62), 234 (89), 220 (100); HRMS: *m*/*z* calcd for $C_{22}H_{27}N$: 305.2143 [M^+]; found: 305.2145.

Acknowledgements

Financial support by the Fonds der Chemischen Industrie (FCI) is gratefully acknowledged.

[1] a) C. S. Yi, *J. Organomet. Chem.* **2011**, *696*, 76–80; b) T. Kondo, *Bull. Chem. Soc. Jpn.* **2011**, *84*, 441–458; c) V. Cadierno, J. Gimeno, *Chem. Rev.* **2009**, *109*, 3512–3560; d) V. Cadierno, P. Crochet, J. Gimeno, *Synlett* **2008**, 1105–1124; e) V. Cadierno, P. Crochet, *Current. Org. Synth.* **2008**, *5*, 343–364; f) J. A. Varela, C. González-Rodriguez, S. G. Rubin, L. Castedo, C. Saá, *Pure Appl. Chem.* **2008**, *80*, 1167–1177; g) M. Arisawa, Y. Terada, K. Takahashi, M. Nakagawa, A. Nishida, *Chem. Rec.* **2007**, *7*, 238–253; h) K. Ohe, *Bull. Korean Chem. Soc.* **2007**, *28*, 2153–2161; i) C. Bruneau, P. H. Dixneuf, *Angew. Chem.* **2006**, *118*, 2232–2260; *Angew. Chem. Int. Ed.* **2006**, *45*, 2176–2203; j) C. Bruneau, S. Dérien, P. H. Dixneuf, *Top. Organomet. Chem.* **2006**, *19*, 295–326; k) B. M. Trost, M. U. Frederiksen, M. T. Rudd, *Angew. Chem.* **2005**, *117*, 6788–6825; *Angew. Chem. Int. Ed.* **2005**, *44*, 6630–6666; l) V. Cadierno, M. P. Gamasa, J. Gimeno, *Coord. Chem. Rev.* **2004**, *248*, 1627–1657; m) *Topics in Organometallic Chemistry, Vol. 11, Ruthenium Catalysts and Fine Chemistry* (Eds.: C. Bruneau, P. H. Dixneuf), Springer, Heidelberg, **2004**.

[2] a) B. M. Trost, A. Breder, *Org. Lett.* **2011**, *13*, 398–401; b) Y. Miyake, S. Endo, Y. Nomaguchi, M. Yuki, Y. Nishibayashi, *Organometallics* **2008**, *27*, 4017–4020; c) H. Matsuzawa, K. Kanao, Y. Miyake, Y. Nishibayashi, *Org. Lett.* **2007**, *9*, 5561–5564; d) Y. Inada, M. Yoshikawa, M. D. Milton, Y. Nishibayashi, S. Uemura, *Eur. J. Org. Chem.* **2006**, 881–890; e) Y. Nishibayashi, Y. Inada, M. Yoshikawa, M. Hidai, S. Uemura, *Angew. Chem.* **2003**, *115*, 1533–1536; *Angew. Chem. Int. Ed.* **2003**, *42*, 1495–1498; f) Y. Nishibayashi, M. Yoshikawa, Y. Inada, M. Hidai, S. Uemura, *J. Am. Chem. Soc.* **2002**, *124*, 11846–11847.

[3] a) G. Aridoss, V. D. Sarca, J. F. Ponder, Jr., J. Crowe, K. K. Laali, *Org. Biomol. Chem.* **2011**, *9*, 2518–2529; b) C. C. Silveira, S. R. Mendes, L. Wolf, G. M. Martins, *Tetrahedron Lett.* **2010**, *51*, 4560–4562; c) M. Zhang, H. Yang, Y. Cheng, Y. Zhu, C. Zhu, *Tetrahedron Lett.* **2010**, *51*, 1176–1179; d) W. Rao, X. Zhang, E. M. L. Sze, P. W. H. Chan, *J. Org. Chem.* **2009**, *74*, 1740–1743; e) J. S. Yadav, B. V. S. Reddy, K. V. R. Rao, G. G. K. S. N. Kumar, *Tetrahedron Lett.* **2007**, *48*, 5573–5576; f) J. S. Yadav, B. V. S. Reddy, K. V. R. Rao, G. G. K. S. N. Kumar, *Synthesis* **2007**, 3205–3210; g) U. Jana, S. Maiti, S. Biswas, *Tetrahedron Lett.* **2007**, *48*, 7160–7163; h) Z. Zhan, J. Yu, H. Liu, Y. Cui, R. Yang, W. Yang, J. Li, *J. Org. Chem.* **2006**, *71*, 8298–8301; i) Z. Zhan, W. Yang, R. Yang, J. Yu, J. Li, H. Liu, *Chem. Commun.* **2006**, 3352–3354; j) R. Sanz, D. Miguel, A. Martinez, M. Gohain, P. Garcia-Garcia, M. A. Fernández-Rodriguez, E. Álvarez, F. Rodriguez, *Eur. J. Org. Chem.* **2010**, 7027–7039; k) P. Srihari, D. C. Bhunia, P. Sreedhar, S. S. Mandal, J. S. S. Reddy, J. S. Yadav, *Tetrahedron Lett.* **2007**, *48*, 8120–8124.

[4] a) E. Haak, *Synlett* **2006**, 1847–1848; b) E. Haak, *Eur. J. Org. Chem.* **2007**, 2815–2824; c) E. Haak, *Eur. J. Org. Chem.* **2008**, 788–792; d) S. Berger, E. Haak, *Tetrahedron Lett.* **2010**, *51*, 6630–6634.

[5] C. P. Casey, X. Jiao, I. A. Guzei, *Organometallics* **2010**, *29*, 4829–4836.

[6] $C_{24}H_{20}N_2O_4Ru$; M_r = 501.49; crystal dimensions: 0.20 × 0.09 × 0.09 mm^3; orthorhombic; space group: $P2_12_12_1$; unit-cell dimensions: a = 9.0210(18), b = 13.488(3), c = 17.599(4) Å; α = 90, β = 90, γ = 90°; cell volume: 2141.4(7) $Å^3$; Z = 4; ρ_{calcd} = 1.556 Mg/m^3; μ = 0.765 mm^{-1}; λ = 0.71073 Å; T = 143(2) K; measured reflections: 13760; independent reflections: 5188; $R_{int.}$ = 0.0803; $R[I>2\sigma(I)]$: $R1$ = 0.0524, $wR2$ = 0.0657; R (all data): $R1$ = 0.0777, $wR2$ = 0.0704.

[7] a) S. Datta, C.-L. Chang, K.-L. Yeh, R.-S. Liu, *J. Am. Chem. Soc.* **2003**, *125*, 9294–9295; b) V. Cadierno, M. P. Gamasa, J. Gimeno, C. González-Bernardo, *Organometallics* **2001**, *20*, 5177–5188; c) E. Bustelo, M. Jiménez-Tenorio, M. C. Puerta, P. Valerga, *Eur. J. Inorg. Chem.* **2001**, 2391–2398; d) D. Wang, D. Chen, J. X. Habermann, C.-J. Li, *Tetrahedron* **1998**, *54*, 5129–5142; e) M. Wang, C.-J. Li in *Topics in Organometallic Chemistry, Vol. 11, Ruthenium Catalysts and Fine Chemistry* (Eds.: C. Bruneau, P. H. Dixneuf), Springer, Heidelberg, **2004**, pp. 321–341.

[8] a) *X-AREA Program for Xray Crystal Data Collection* (*X-RED32* included in *X-AREA*), Stoe & Cie, Darmstadt, **2002**; b) G. M. Sheldrick, *SHELXS-97 Program for Crystal Structure Solution*, Universität Göttingen, Göttingen, **1997**; c) G. M. Sheldrick, *SHELXL-97 Program for Crystal Structure Refinement*, Universität Göttingen, Göttingen, **1997**.

[9] a) First reported by S. L. Shapiro, L. Freedman (U. S. Vitamin and Pharmaceutical Corp., New York), US 2993890, **1961**; b) First reported by W. A. Remers, R. H. Roth, G. J. Gibs, M. J. Weiss, *J. Org. Chem.* **1971**, *36*, 1232–1240.

Received: January 17, 2012
Published online: April 4, 2012

