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Hydroacenes Made Easy by Gold(I) Catalysis

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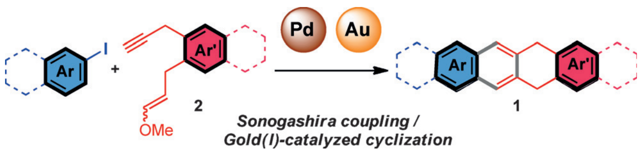
Abstract: *A novel strategy for the synthesis of partially saturated acene derivatives has been developed based on a Au^{I}-catalyzed cyclization of 1,7-enynes. This method provides straightforward access to stable polycyclic products featuring the backbone of the acene series, up to nonacene.*

Acenes—a class of polycyclic aromatic hydrocarbons (PAHs) made up of *n* linearly fused benzene rings—have been extensively studied in recent years on account of their distinctive electronic properties, which make them attractive candidates for use in molecular electronics.[1] However, the application of the higher acenes ($n \geq 6$) as functional materials is limited by the rapid decrease of both solubility and stability as the number of annealed rings grows.[2] Although syntheses of the parent acenes have been reported up to and including nonacene ($n = 9$), the low stability of the higher acenes makes isolation a formidable challenge, requiring inert matrices.[3] One of the most common strategies to curb the intrinsic photo-instability of the higher acenes is the attachment of suitable stabilizing substituents,[4] predominantly bulky groups close to the most reactive central rings. Nevertheless, many of these derivatives still suffer from decomposition, even in dilute solution. Another approach to circumvent acene instability is the use of protecting groups that reduce their reactivity, allowing for long-term storage as well as imparting additional solubility, before deprotection reveals the acene.[3,5] In this regard, partially saturated acenes, which have been extensively employed as direct precursors of the corresponding fully conjugated acenes,[3c,6] can be considered to be "hydrogen-protected",[7] exhibiting improved solubilities and excellent stabilities. The synthesis of partially hydrogenated acene derivatives has been achieved by direct reduction of the corresponding acenes or quinones.[7,8] However, these methods often require harsh conditions and are prone to produce regioisomeric mixtures. Therefore, general methods to selectively obtain partially saturated acenes still remain elusive.

Cyclizations of enynes catalyzed by gold(I) complexes have emerged over the last decade as one of the most powerful tools to construct complex polycyclic architectures from relatively simple substrates under mild reaction conditions,[9] and they have been successfully applied to the synthesis of functionalized aromatic frameworks.[10] We have reported the cyclization of 1,6- and 1,7-enynes bearing an aryl substituent at the alkyne terminus in the presence of gold(I), respectively affording naphthalene and polyhydrogenated anthracene derivatives through formal [4+2] cycloadditions.[11] The cyclizations of certain 1,7-enynes, bearing an aryl group bonded to the alkene, also afford polyhydrogenated anthracenes in the presence of gold(I) at high temperatures.[12] Herein, we report ready access to stable functionalized higher hydroacenes **1** through the gold(I)-catalyzed cyclization of suitable 1,7-enynes in which the alkene is part of an enol ether function.

We envisioned that the gold(I)-catalyzed cyclization of the 1,7-enynes that result from a palladium-catalyzed Sonogashira cross-coupling between an aryl iodide and key precursors **2**, would afford hydroacenes **1** upon aromatization by elimination of a molecule of methanol (Scheme 1). By combining these two robust and broad scope metal-catalyzed methods, a wide variety of linear hydroacenes **1** could in principle be obtained by annulation of a wide range of readily available aryl iodides.



Scheme 1. Conceptual approach to hydroacenes.

The simplest 1,7-enyne **3a**, which was assembled from iodobenzene and **2a**, was chosen as the model substrate to explore the gold(I)-catalyzed cyclization to form 5,12-dihydrotetracene (**1a**; Table 1). The cyclization of **3a** was first examined at 25 °C in the presence of cationic gold(I) complexes **A**–**C** (10 mol %), spanning a wide range of electrophilicity. Gratifyingly, all three gold complexes successfully delivered the desired dihydrotetracene **1a** as the major product. The most electrophilic catalyst **C** caused the concomitant formation of a rearrangement byproduct in approximately 15 % yield, as determined by NMR spectroscopy, whereas the only identifiable byproduct in the reactions with complexes **A** and **B** was tetracycle **1a′**, which is an intermediate during the formation of **1a**.[13] Thus, commercially available JohnPhos–Au^{I} catalyst **A** was selected for further optimization. Lowering the catalyst loading to 5 mol % (Table 1, entry 4) increased the amount of **1a′** that remained, even when extended reaction times were employed. Complete consumption of **1a′** was achieved by

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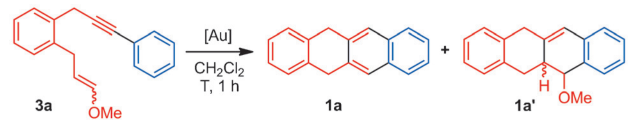
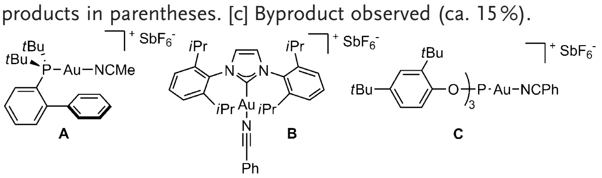
Table 1: Optimization of the gold(I)-catalyzed cyclization of **3a**.[a]



Entry	[Au] [mol%]	*T* [°C]	Yield **1a** [%][b]	Yield **1a′** [%][b]
1	**A** (10)	25	95	5
2	**B** (10)	25	95	5
3	**C** (10)	25	85[c]	0
4	**A** (5)	25	75	25
5	**A** (5)	40	≥99 (96)	0
6	**A** (2.5)	40	≥99 (95)	0
7	**A** (1)	40	90 (84)	10

[a] Yield determined by ^{1}H NMR spectroscopy. [b] Yields of isolated products in parentheses. [c] Byproduct observed (ca. 15%).

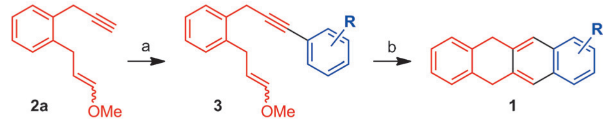


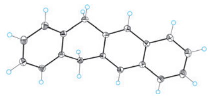
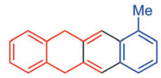
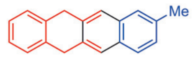
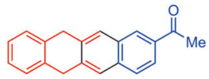
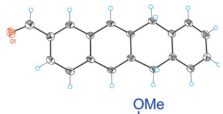
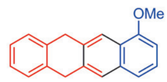
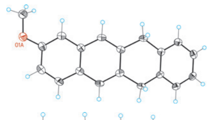
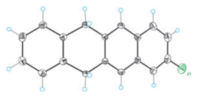
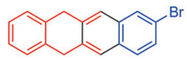
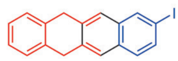
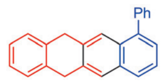
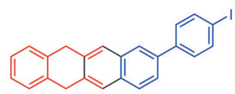
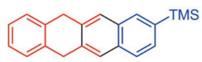
heating the reaction at 40°C, which drove the reaction to completion (Table 1, entry 5), even at lower catalyst loadings down to 2.5 mol%. Under the optimized reaction conditions (Table 1, entry 6) 5,12-dihydrotetracene (**1a**), which could be converted quantitatively into the parent acene,[6f] was isolated in 95% yield.

The substrate generality for the synthesis of functionalized dihydrotetracenes was examined (Table 2) under these optimized reaction conditions. Thus, starting from **2a**[14] as the common precursor, a series of enynes **3** were prepared under standard Sonogashira cross-coupling conditions starting from substituted iodobenzenes, before being subjected to the gold(I)-catalyzed cyclization. In general, good to excellent yields (46–99%) were obtained for the 1,7-enynes tested. Enynes bearing both electron-rich and electron-poor aryl groups at the alkyne terminus efficiently afforded the corresponding dihydrotetracenes. 7-Substituted 5,12-dihydrotetracenes were selectively accessed from *ortho*-substituted iodobenzenes (**1b**, **1f**, **1k**), whereas 1,7-enynes derived from *para*-substituted iodobenzenes provided 8-substituted 5,12-dihydrotetracenes (**1c–e**, **1g–j**, **1l**,**m**). Several 5,12-dihydrotetracene derivatives were prepared bearing carbonyl (**1d**,**e**) or halide (**1h–j**, **1l**) groups, which are convenient functional handles for further synthetic manipulations. Although the cyclization of *meta*-substituted enynes also provided dihydroacenes, the expected mixtures of regioisomeric 7- and 8-substituted 5,12-dihydrotetracenes were obtained, and therefore these substrates were not explored further.

The gold(I)-catalyzed cyclization was applied to the preparation of extended PAHs and partially hydrogenated heteroacenes (Table 3). Dihydrobenzotetracene **1n**, dihydrodibenzotetracene **1o**, and dihydronaphthopentacene **1p** were prepared in good to excellent yields by cyclization of the enynes resulting from the coupling of **2a** with 2-iodonaphthalene, 9-iodophenanthrene, and 1-iodopyrene,

Table 2: Scope of the gold(I)-catalyzed cyclization of 1,7-enynes **3** to form dihydrotetracenes.[a]



Entry	R	**3** [% yield]		**1** [% yield]
1	H	**3a** (95)		**1a** (95)
2	2-Me	**3b** (72)		**1b** (68)
3	4-Me	**3c** (67)		**1c** (54)
4	4-COMe	**3d** (88)		**1d** (59)
5	4-CHO	**3e** (73)		**1e** (71)
6	2-OMe	**3f** (86)		**1f** (77)
7	4-OMe	**3g** (86)		**1g** (60)
8	4-F	**3h** (99)		**1h** (76)
9	4-Br	**3i** (88)		**1i** (67)
10	4-I	**3j** (55)		**1j** (99)
11	2-Ph	**3k** (60)		**1k** (46)
12	4(4-IC_6H_4)	**3l** (46)		**1l** (71)
13	4-$SiMe_3$	**3m** (82)		**1m** (55)

[a] Reaction conditions: a) ArI, $PdCl_2(PPh_3)_3$, CuI, Et_3N, 40°C, 1.5 h. b) **A** (2.5 mol%), CH_2Cl_2, 40°C, 1 h. ORTEP plots (50% thermal ellipsoids) of the X-ray crystal structures of **1a**, **1e**, **1g**, and **1h** are shown. Atoms: oxygen (red), fluorine (green), hydrogen (white), carbon (gray).[15]

respectively. Dihydroheteroacenes **1q** and **1r** were similarly obtained from 2-iodothiophene and 2-iodobenzothiophene. Moreover, expanded precursors **2b** and **2c** bearing additional fused benzene rings could be employed successfully to synthesize dihydrodibenzotetracene **1s** and dihydropentacene **1t**, respectively.

To further illustrate the potential of this gold(I)-catalyzed cyclization method, di- and tri-1,7-enynes were prepared from terminal alkynes **2a–c** and the corresponding di- and triiodoarenes. Interestingly, these polyenynes underwent the desired multiple gold(I)-catalyzed cyclizations under the

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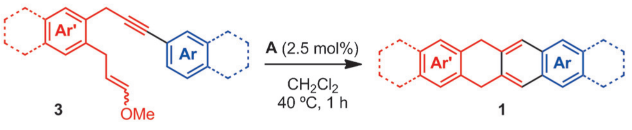
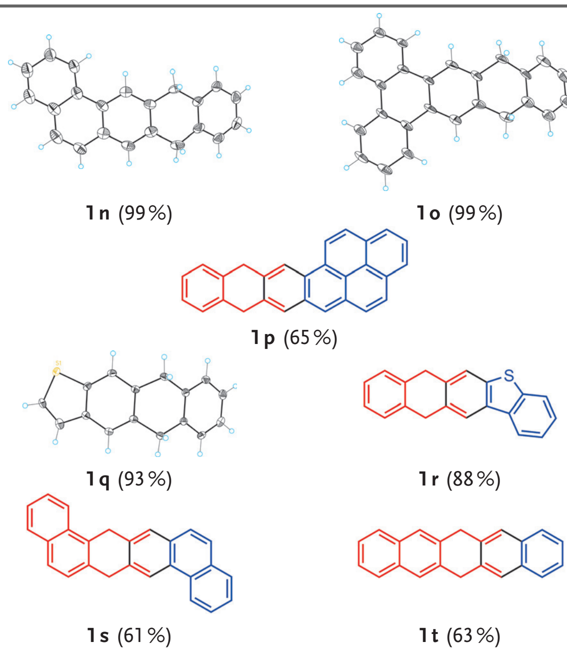
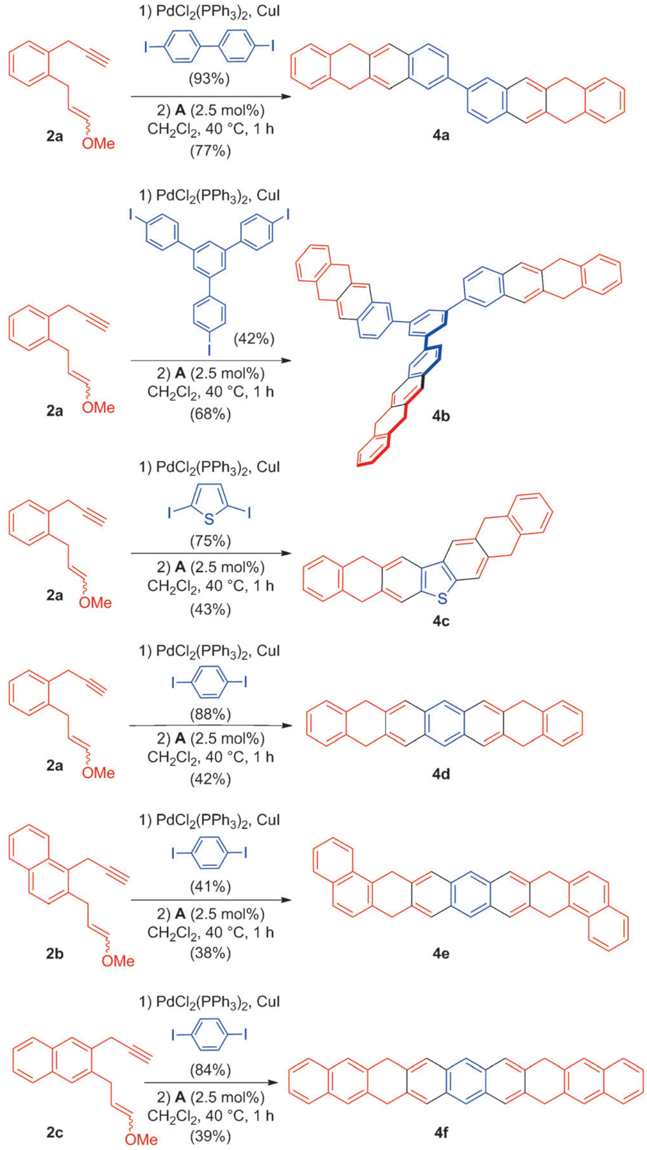
Table 3: Synthesis of expanded dihydroPAHs and dihydroheteroacenes.[a]





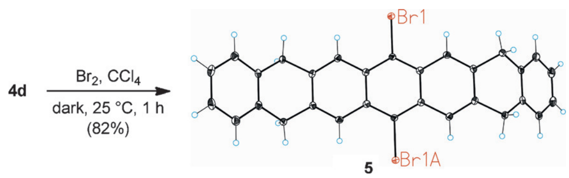
[a] ORTEP plots (50% thermal ellipsoids) of the crystal structures of **1n**, **1o**, and **1q**. Atom colors are the same as those in Table 2; the sulfur atom of **1q** is shown in yellow.[14]



Scheme 2. Synthesis of polyhydroacenes by multiple gold(I)-catalyzed cyclizations.

reaction conditions optimized for the cyclization of **3a** to cleanly afford products **4** (Scheme 2). Poly-dihydrotetracenes **4a** and **4b** were thus prepared, providing a new route to stable and relatively soluble precursors of acene-based materials, which have shown good performance as *n*-type materials in organic field-effect transistors.[16] Similarly, the double cyclization of a dienyne derived from 2,5-diiodothiophene afforded **4c**, which is known to be a precursor of a fully aromatic sulfur-containing heptacene analogue.[17] Most remarkable was the double cyclization of dienynes derived from 1,4-diiodobenzene, which regioselectively provided compounds **4d–f** as the sole products, constituting isolable, stable derivatives of heptacene, dibenzo[*a*,*p*]heptacene, and nonacene, respectively.

To confirm the structure of **4d**, crystalline dibromo derivative **5** was prepared and its structure was unambiguously assigned by X-ray diffraction analysis (Scheme 3). Thus, not only was the linearity of **4d** confirmed, but a potential entry to functionalized larger hydroacenes was generated.



Scheme 3. Dibromination of **4d**. ORTEP plot (50% thermal ellipsoids) of the crystal structure of **5**. Atom colors are the same as those in Table 2; bromine atoms are shown in orange.[14]

In summary, we have developed a versatile annulation for the preparation of partially saturated acene derivatives based on a Sonogashira coupling and a gold(I)-catalyzed cyclization of aryl-tethered 1,7-enynes **3**, which takes place efficiently under mild reaction conditions and tolerates a range of functionalities. Furthermore, double and triple cyclizations can be performed on suitable polyenynes, allowing the assembly of the backbone of larger acenes up to nonacene. Investigations into the metal surface-assisted aromatization of larger hydroacenes to obtain the corresponding parent acenes and the synthesis of new annulation synthons are currently underway.

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Keywords: 1,7-enynes · acenes · cycloaddition · gold(I) catalysis · Sonogashira coupling

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[13] For a detailed mechanistic scheme of the gold(I)-catalyzed cyclization see the Supporting Information.

[14] Synthon **2a** was prepared from 1-bromo-2-(3-methoxyallyl)benzene and methoxyallene, according to: J. Meijer, P. Vermeer, *Rec. Trav. Chim. Pays Bas* **1974**, *93*, 183. See the Supporting Information.

[15] CCDC 1475950 (**1a**), CCDC 1475951 (**1e**), CCDC 1475952 (**1g**), CCDC 1475953 (**1h**), CCDC 1475954 (**1n**), CCDC 1475955 (**1o**), CCDC 1475956 (**1q**) and CCDC 1476286 (**5**), contain 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.

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