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Development of novel synthetic routes to bis(perfluoroalkyl)-substituted anthracene derivatives†

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Shigeyuki Yamada,[a] Keita Kinoshita,[a] Shota Iwama,[a] Takashi Yamazaki,*[a]
Toshio Kubota[b] and Tomoko Yajima[c]

Commercially available anthraquinones were smoothly converted to either symmetrically or unsymmetrically substituted 9,10-bis(perfluoroalkyl)anthracene-9,10-diols by way of bistrifluoromethylation or successive trifluoromethylation-nucleophilic perfluoroalkylation, respectively, and these diols can be easily aromatized to form bis(perfluoroalkyl)anthracene derivatives in good yields by treatment with a mixture of CBr_4 and PPh_3. Further cross-coupling reactions using halogen-containing anthracene derivatives realized a successful extension of the original π-conjugation systems.

Acenes, represented by anthracenes with linearly fused benzene rings, are well-known as a family of polycyclic aromatic hydrocarbons (PAHs) which have been drawing enormous interest as important materials for a variety of organic electronic devices[1,2] by utilization of their characteristics, like light weight, flexibility, ready structural modification, and so forth.[3] Functionalization of the anthracene backbone is one of the most straightforward and facile methods to affect the original quality, and various elements as well as groups have been introduced to this structure. Among them, perfluoroalkyl (Rf) moieties are quite intriguing due to their strong electron-withdrawing nature which would effectively lower the HOMO and LUMO energy levels as well as affect good alignment by steady intermolecular electrostatic interactions, leading to the construction of a higher-ordered stacking structure (Fig. 1). While Rf-substituted anthracenes have been synthesized by a few groups,[4] to the best of our knowledge no reports have appeared thus far on their preparation with two different Rf moieties at 9 and 10 positions. In this communication, we disclose a new and effective approach to the preparation of various types of Rf-containing anthracenes by less than 4 facile steps.

Our approach for this purpose consists of the following three reaction steps: (1) nucleophilic addition of CF_3SiMe_3 to 9,10-anthraquinones, followed by RfLi, (2) hydrolysis of the resultant silyl ethers, and (3) reductive aromatization (Scheme 1).

Our study was initiated by the synthesis of symmetrical bis(trifluoromethyl)anthracenes (**3**) with reference to the previously reported conditions,[5] using CF_3SiEt_3 as the CF_3 source for the reaction with anthraquinones (**1**) in the presence of K_2CO_3 as an activator. In our instance, due to its ready availability, 3.0 equiv. of Ruppert–Prakash reagent (CF_3SiMe_3)[6] was subjected to a DMF solution of 9,10-anthraquinone (**1a**) in the presence of 0.4 equiv. of K_2CO_3 at room temperature, and after 15 h, the corresponding bis(trifluoromethyl)adduct was obtained in 82% yield.[7] Incorporation of other Rf groups such as C_4F_9 or C_6F_{13} to **1a** by way of the corresponding lithium species was found unsuccessful, possibly due to their low thermal stability and nucleophilicity along with low solubility of **1a** at the reaction temperature of -80 °C. This silylated adduct was easily hydrolysed by exposure to concentrated hydrochloric acid, leading to the exclusive formation of 9,10-bis(trifluoromethyl)anthracene-9,10-diol (**2a**) in 96% yield with the *anti* configuration as the sole stereoisomer[7] (71% yield in 2 steps from **1a**). While the usual aromatization conditions, like $SnCl_2$ with HCl, did not work at all,[8] smooth transformation of the diol **2a** was realized by treatment with a mixture of CBr_4 and PPh_3 (3.0 and 4.5 equiv., respectively) in CH_2Cl_2 at rt for 15 h to produce the desired 9,10-bis(trifluoromethyl)anthracene (**3a**) in 66% yield (entry 1, Table 1). As shown in entries 2–5, the above

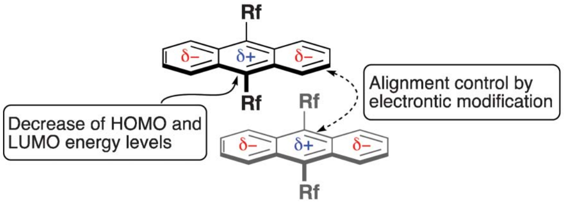

Fig. 1 Possible effects of perfluoroalkyl groups on anthracenes.

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[a] *Department of Applied Chemistry, Graduate School of Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakamachi, Koganei 184-8588, Japan. E-mail: tyamazak@cc.tuat.ac.jp*

[b] *Department of Biomolecular Functional Engineering, Ibaraki University, Nakanarusawa 4-12-1, Hitachi 316-8511, Japan. E-mail: t.kubota@mx.ibaraki.ac.jp*

[c] *Department of Chemistry, Faculty of Science, Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo 112-8610, Japan. E-mail: yajma.tomoko@ocha.ac.jp*

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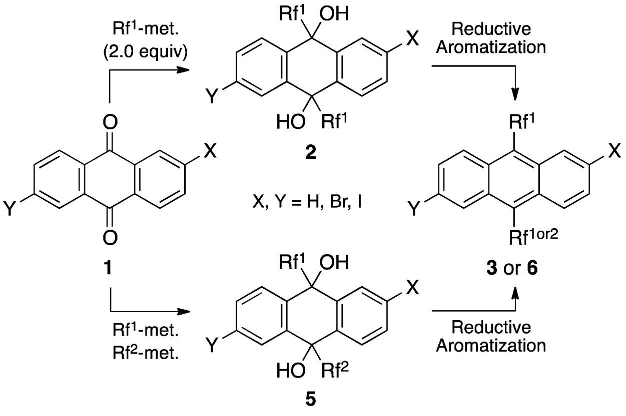
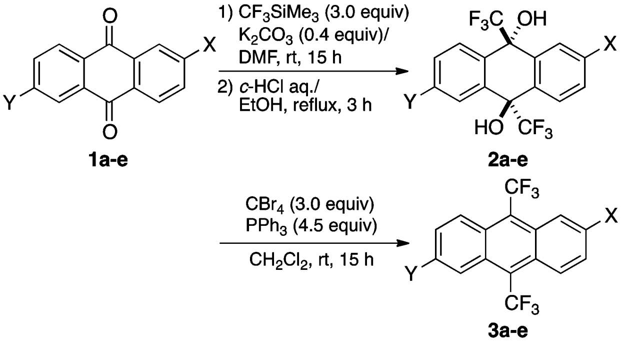


Scheme 1 Outline of our approach to Rf-substituted anthracenes.

bistrifluoromethylation protocol was also examined towards 2-mono or 2,6-dihalogenated substrates **1b–e**, prepared in good yields by the well-known Sandmeyer reaction of the corresponding commercially available NH_2-possessing counterparts (52–80%). The diols with two CF_3 groups **2b–e** were obtained by subjecting **1b–e** to the similar nucleophilic trifluoromethylation conditions, followed by hydrolysis. Conversion of the intermediary silyl ether from **1e** was the special case, not effectively giving the corresponding diol **2e**, while deprotection was facilitated by tetrabutylammonium fluoride (TBAF), allowing isolation of **2e** in 74% total yield from **1e**. Aromatization of these products **2b–e** with halogen atoms was similarly operated to form the corresponding anthracenes **3b–e** in 52–94% yields.

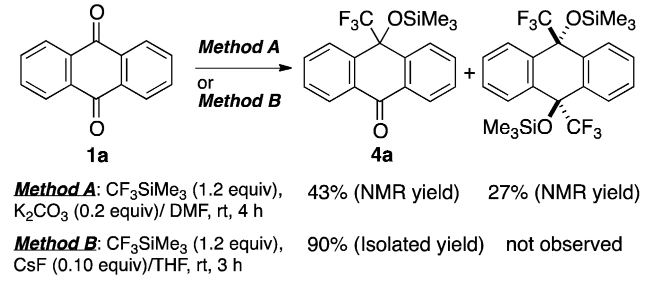
At the next stage, our interest was focused on the synthesis of hitherto unknown unsymmetrical bis(perfluoroalkyl)anthracenes. As described above, since direct introduction of Rf groups with the aid of RfLi met with difficulty, our strategy was to start from the monotrifluoromethylation of **1**, which would offer higher solubility of the product due to the unsymmetrical substitution pattern, rendering a better chance of acceptance to attack by these nucleophiles, even at a low temperature.

Table 1 Synthesis of 9,10-bis(trifluoromethyl)anthracenes **3** from **1**



Entry	X, Y in **1**	Yield of **2** (%)[a]	Yield of **3** (%)[a]
1	H, H (**1a**)	71 (**2a**)	66 (**3a**)
2	Br, H (**1b**)	Quant (**2b**)	94 (**3b**)
3	I, H (**1c**)	Quant (**2c**)	52 (**3c**)
4	Br, Br (**1d**)	85 (**2d**)	73 (**3d**)
5	I, I (**1e**)	74[b] (**2e**)	84 (**3e**)

[a] Isolated yields. [b] Tetrabutylammonium fluoride was used instead of c-HCl aq.



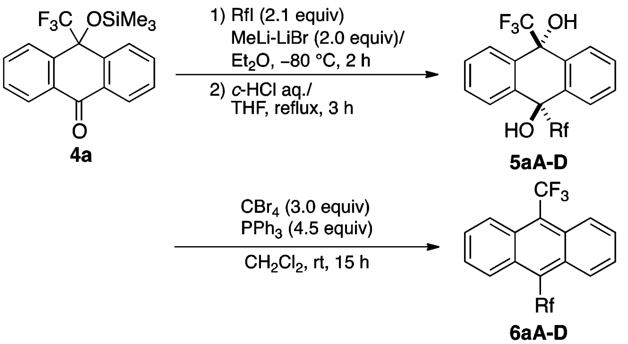
Scheme 2 Preparation of mono-trifluoromethylated substrate **4a**.

Initially, incorporation of only one CF_3 moiety to **1a** was conducted by the above bistrifluoromethylation procedure with control over the reagent amount (Method A in Scheme 2), which smoothly proceeded to form the desired adduct **4a** in 43% yield, together with 27% of bis(trifluoromethyl) adduct. After intensive examination,[9] the slow addition of a slight excess of CF_3SiMe_3 (1.2 equiv.) to a THF solution of **1a** containing 0.10 equiv. of CsF was found to be quite effective, and the following stirring at rt for 3 h (Method B) furnished the desired mono-trifluoromethyl adduct **4a** in excellent 90% isolated yield.

To the obtained **4a**, the nucleophilic addition of *in situ* generated RfLi was then carried out by dropwise addition of a MeLi–LiBr complex to an Et_2O solution of **4a** and perfluorobutyl iodide at -80 °C.[10] This reaction took place smoothly with stirring for 2 h at the same temperature to afford the corresponding adduct in 79% yield, which led to the formation of a differently-substituted 9,10-diol **5aA** in 79% yield (62% yield in 2 steps from **4a**) after simple acidic hydrolysis in the same manner (entry 1, Table 2). This diol, **5aA**, was successfully converted to the corresponding unsymmetrical 9,10-bis(perfluoroalkyl)anthracene **6aA** in 93% yield *via* our reductive aromatization conditions (CBr_4–PPh_3). As shown in entries 2–4, the representative mono-trifluoromethyl adduct **4a** successfully accepted nucleophilic attack by such lithium species as $C_6F_{13}Li$, $C_8F_{17}Li$, and $C_{10}F_{21}Li$, and further deprotection to 9,10-diols **5aB–D** was realized in 42%–57% yields by the same procedure. Their subsequent reductive aromatization was also found to proceed well to provide the unprecedented unsymmetrical anthracenes **6aB–D** in good yields.

Fortunately, the unsymmetrically 9,10-perfluoroalkylated anthracene **6aB** furnished a single crystal appropriate for X-ray crystallographic analysis, and the structure obtained is illustrated in Fig. 2. It is interesting to note that one fluorine atom in the CF_3 group in **6aB** occupied the vertical position to the aromatic backbone (F-C-C-C dihedral angle of 89.8°), which might bring about a slight bend of the anthracene core, possibly for reducing the undesired repulsive interaction between fluorine and hydrogen atoms at the *peri* position (Fig. 2a).[11] A unit cell consisted of four molecules, two of which were π-stacked so as to enable the electrostatic interaction of the electron-deficient central ring with

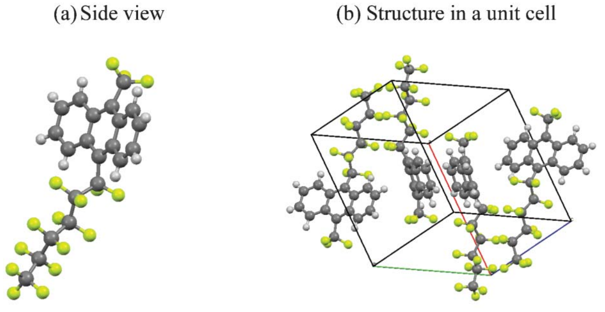
Table 2 Synthesis of unsymmetrical 9,10-bis(perfluoroalkyl)anthracene derivatives from mono-trifluoromethyl adduct **4a**



Entry	Rf	Yield of **5a** (%)[a]	Yield of **6a** (%)[a]
1	C_4F_9	62 (**5aA**)	93 (**6aA**)
2	C_6F_{13}	52 (**5aB**)	64 (**6aB**)
3	C_8F_{17}	57 (**5aC**)	74 (**6aC**)
4	$C_{10}F_{21}$	42 (**5aD**)	87 (**6aD**)

[a] Isolated yields.

the relatively electron-rich edge part where two C_6F_{13} groups in different molecules point towards opposite directions (Fig. 2b). The other two molecules constituted a C–H···π interaction with the electron-deficient ring, constructing Rf-aggregation known as the "fluorophilic effect".[12] Packing of these compounds was found to be relatively tight, which was supported by the shortest C–C (between two stacking anthracene rings) and C–H (between one anthracene central ring carbon and the other anthracene hydrogen) distances of 333 and 275 pm, respectively, both of which are below the sum of the van der Waals radii.[13] The structure of **6aB** shown in (c) in Fig. 2 clearly indicates the presence of the fluorophilic effect between neighbouring C_6F_{13}-chains, whose F–F distance (301 pm) is only 7 pm longer than the sum of van der Waals radii.


(a) Side view

(b) Structure in a unit cell

(c) A packing structure

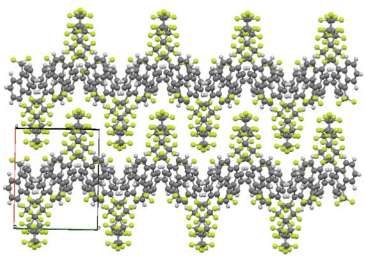
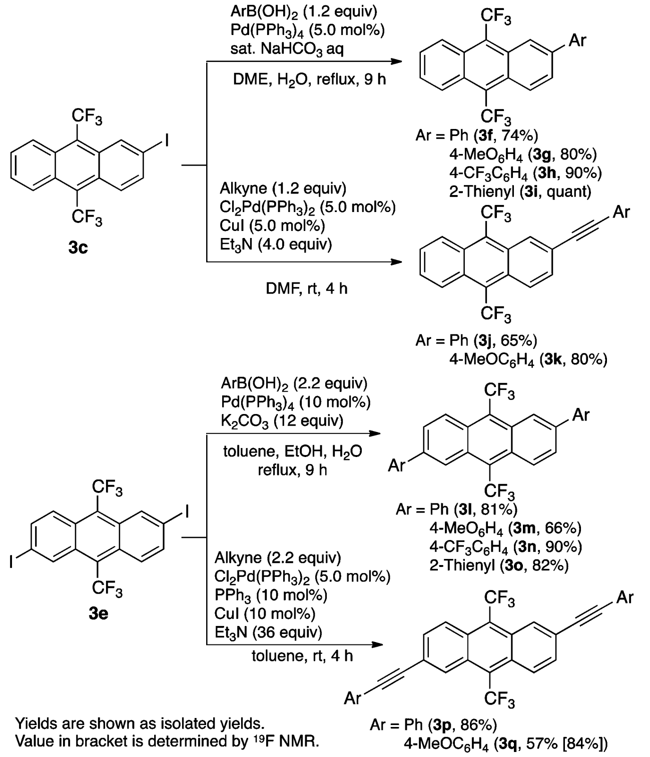


Fig. 2 Crystal structure of **6aB**.

For clarification of the usefulness of the "halogen handle" at the benzene ring for assembly of the extended π-conjugate systems, we attempted the palladium-catalyzed introduction of substituents with sp^2- or sp-carbon reaction sites as illustrated in Scheme 3. Thus, 2-iodo- (**3c**) and 2,6-diiodo-9,10-bis(trifluoromethyl)anthracenes (**3e**) as the model compounds were subjected to the well-accepted cross-coupling reactions with arylboronic acids (Suzuki–Miyaura)[14] or terminal alkynes (Sonogashira),[15] leading to 2-aryl- (**3f–i**), 2-arylethynyl- (**3j–k**), 2,6-diaryl- (**3l–o**), and 2,6-bis(arylethynyl)-substituted anthracenes (**3p–q**) in good to excellent yields.

Conclusions

In conclusion, we have developed a new synthetic pathway not only to symmetrical bis(trifluoromethyl)anthracenes but also to hitherto unknown unsymmetrically perfluoroalkyl-substituted counterparts at the 9 and 10 positions, both of which were formed from the corresponding anthraquinones in less than four easy steps. Moreover, 2-iodinated and 2,6-diiodinated bis(trifluoromethyl)anthracenes as the representative examples were subjected to Suzuki–Miyaura and Sonogashira cross-coupling reactions, achieving the incorporation of various types of substituents with π-conjugate systems. Crystallographic data of



Yields are shown as isolated yields.
Value in bracket is determined by ^{19}F NMR.

Scheme 3 Synthetic application of 2-iodo- (**3c**) or 2,6-diiodoanthracene derivatives (**3e**) to CF_3-containing π-conjugate systems.

6aB unambiguously clarified the effectiveness of our concept, where Rf groups properly work for construction of a regular arrangement of acene molecules. Further studies on the preparation and structural characterization of a variety of perfluoroalkyl-substituted acenes are currently under investigation in our laboratory.

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