An Intramolecular Iodine-Catalyzed C(sp³)—H Oxidation as a Versatile Tool for the Synthesis of Tetrahydrofurans

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In memory of the early death of Kilian Muñiz.

The formation of ubiquitous occurring tetrahydrofuran patterns has been extensively investigated in the 1960s as it was one of the first examples of a non-directed remote C—H activation. These approaches suffer from the use of toxic transition metals in overstoichiometric amounts. An attractive metal-free solution for transforming carbon-hydrogen bonds into carbon-oxygen bonds lies in applying economically and ecologically favorable iodine reagents. The presented method involves an intertwined catalytic cycle of a radical chain reaction and an iodine(I/III) redox couple by selectively activating a remote C(sp³)—H bond under visible-light irradiation. The reaction proceeds under mild reaction conditions, is operationally simple and tolerates many functional groups giving fast and easy access to different substituted tetrahydrofurans.

The formation of saturated heterocycles by C—H activation of unactivated C(sp³)—H bonds can look back on a long history of extensive research[1] and be first discovered by Hofmann in the late 1800s for pyridines.[2] His approach was based on forming highly reactive nitrogen-centered radicals from the homolysis of haloamines, activating distant carbon-hydrogen bonds by an intramolecular 1,5-hydrogen atom transfer (HAT).[3,4,5,6] The synthetic value of this reaction was demonstrated more than 25 years later by the elegant synthesis of nicotine by Löffler and Freytag.[7] Analogous reactions based on oxygen radicals were developed a little later, enabling valuable access to tetrahydrofurans (THF). The THF motifs can be found in various natural products and play a crucial role in terpenes and steroids, where THF rings were also intr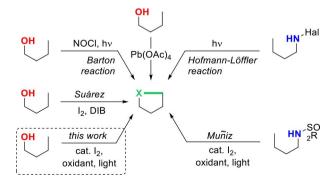oduced as "intermediates" to install an oxygen-functionality to an unactivated methyl group.[8] Alkoxyl radicals initiate this intramolecular remote functionalization of non-activated atoms prepared *in-situ* by different procedures (Scheme 1).[9] For example, they can be generated by the photolysis of nitrite esters (Barton reaction).[10] Alternatively, *O*-centered radicals were prepared *in-situ via* a hypoiodite reaction with heavy metals such as lead tetraacetate (LTA) or by less toxic reagents like an *N*-iodosuccinimide or (diacetoxyiodo) benzene (DIB) (Suárez modification).[11] However, an excess of the oxidizing reagent and equimolar amounts of molecular iodine is required, also leading to undesired overoxidation products.[12] A few years ago, the Togo group reported the synthesis of heterocycle using diiodohydantoins.[13] Recently, the group of Muñiz overcame these drawbacks for the synthesis of pyrrolidines and presented an iodine-catalyzed version of the Hofmann-Löffler reaction using different oxidants and light sources such as DIB analogs,[14] *m*-CPBA with *t*-BuOH[15] or TPT with H₂O and irradiation with blue LEDs.[16] Inspired by this reaction protocol's simplicity and efficacy, we envisioned developing an iodine-catalyzed, remote C—H activation of primary and secondary alcohols to access tetrahydrofurans under mild reaction conditions easily.

We commenced our investigations on the steroidal alcohol 3β-acetoxy-2β-hydroxy-5α-androstan-17-on (**1a**), the key intermediate in the semi-synthesis towards the cardiac glycoside Calotropin.[12,17] Due to the rigid steroidal skeleton, the hydroxyl group and the methyl group to be activated are close to one another, facilitating the C—H activation and the formation of the THF ring (Table 1). Suárez-type reaction conditions with stoichiometric amounts of iodine, commercially available DIB, and

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Scheme 1. Remote C—H functionalization of non-functionalized alcohols (left) and electron-acceptor-substituted amines (right), resulting in heterocyclic 5-membered rings.

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Table 1. Development of the iodine-catalyzed cyclization reaction.

I₂ (x mol%), oxidant (1.00 equiv.), 1,2-DCE, conditions

Entry	Oxidant	I₂ (x [mol %])	Conditions	Yield [%][a]
1	PhI(OAc)₂	100	9 h, 500 W lamp, 45 °C	46[b]
2	PhI(OAc)₂	10	9 h, 500 W lamp, 45 °C	44[b]
3	Ph(m-CBA)₂	10	9 h, 500 W lamp, 45 °C	77
4	Ph(m-CBA)₂	5	9 h, 500 W lamp, 45 °C	35[b]
5	Ph(m-CBA)₂	100	2 d, day light, rt	78
6	Ph(m-CBA)₂	10	2 d, day light, rt	60
7	Ph(m-DCBA)	10	9 h, 500 W lamp, 45 °C	78
8	Ph(m-DMBA)₂	10	9 h, 500 W lamp, 45 °C	60
9	Ph(PFBA)₂	10	9 h, 500 W lamp, 45 °C	68
10	Ph(m-CBA)₂	0	9 h, 500 W lamp, 45 °C	0
11	Ph(m-CBA)₂	10	9 h, darkness, 45 °C	0
12	Ph(m-CBA)₂	10	9 h, 500 W lamp, 45 °C	60[c]

[a] Yields refer to isolated material of **1b** after purification. [b] Starting material was recovered. [c] Reaction in the presence of 5.0 equiv. m-CBAH. 1,2-DCE = 1,2-dichloroethane, m-CBA = 3-chlorobenzoate, m-DCBA = 3,5-dichlorobenzoate, m-DMBA = 3,5-dimethylbenzoate, PFBA = 2,3,4,5,6-perfluorobenzoate

irradiation with a 500 W halogen lamp were applied to deliver the product **1b** in a moderate yield of 46% (entry 1). Upon lowering the amount of iodine to 10 mol%, a similar yield of 44% was obtained (entry 2). Changing the iodine(III) reagent to PhI(m-CBA)₂ (m-CBA = 3-chlorobenzoate) under otherwise identical catalytic reaction conditions provided product **1b** with a very good yield of 77% (entry 3).

When lowering the amount of iodine to 5 mol%, the reaction seems to proceed slower, giving the product in 35% yield (entry 4). The reaction can also be carried out at room

temperature and exposure to daylight with PhI(m-CBA)₂ as oxidant, with the same yield under artificial irradiation (entries 5 and 6). Even though the cyclization reaction works better with stoichiometric amounts of iodine (entry 5), affording the product with 78% yield, good yields of 60% were also isolated with catalytic amounts of iodine (entry 6). Nevertheless, the reaction seems to proceed slower and require longer reaction times. No further optimization could be achieved by fine-tuning the electronic properties of iodine(III) reagents. Neither by changing the substituents on the aryl moiety to a more electron-withdrawing nor an electron-donating substituent had the desired effect (entries 7–9). With the presented cyclization reaction, the need for an excess of a terminal oxidant is no longer required. In combination with the use of catalytic amounts of iodine, this results in a much cleaner reaction outcome than comparable protocols leading to overoxidation. Without either iodine (entry 10) or light (entry 11), no conversion of the starting material was detected. Additionally, the reaction can also be conducted with defined LED irradiation (see ESI chapter 2.3.3), but to keep the reaction set-up operationally simple, we preferred using a simple halogen lamp as a light source.

As previously reported for iodine-catalyzed Hofmann-Löffler reactions,[18] it is initiated by the formation of the active catalyst I(mCBA) from molecular iodine and the hypervalent iodine(III) reagent (Scheme 2). We propose the in-situ formation of a hypoiodite accompanied by the formation of the corresponding carboxylic acid m-CBAH. Contrary to the results of the Muñiz group, which showed a stabilizing effect of carboxylic acid by the formation of I(m-CBA)·m-CBAH adduct,[14] we detected a slight drop in yield in the presence of five equivalents of m-CBAH (Table 1, entry 12) indicating that in our case the free carboxylic acid influences the reaction mechanism. However, the photochemical decomposition of the alkoxy radical gives

Scheme 2. Proposed reaction mechanism for the iodine-catalyzed cyclization reaction.

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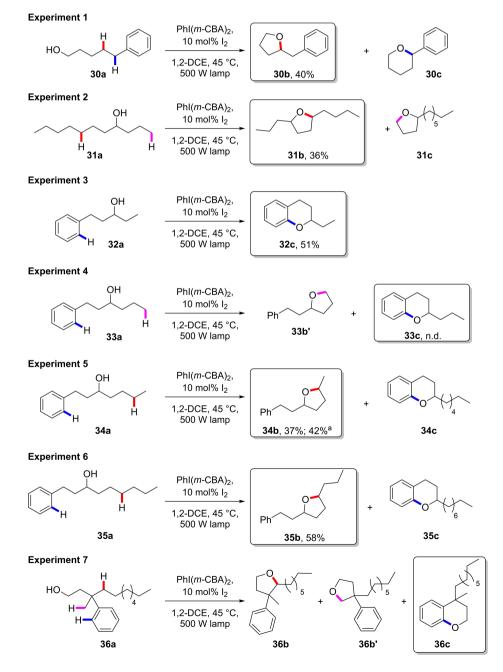Europe**
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the *O*-centered radical that can abstract a hydrogen atom from a spatially close C—H group in δ-position, in this case, the C-19 methyl group. After recombination of the radicals, the carbon atom is oxidized by the hypervalent iodine(III) reagent followed by a nucleophilic attack of the 2-hydroxy group, which is due to the increased leaving group ability of iodine(III) comparatively fast (e.g., compared with the direct oxygenation) resulting in the formation of the THF ring and the regeneration of the active catalyst.
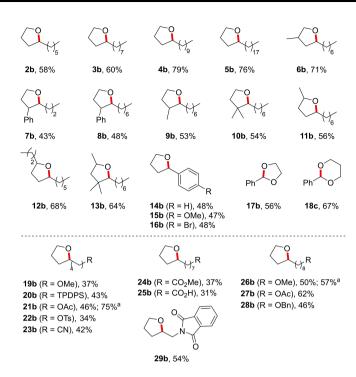
Next, we were keen to explore whether the reaction can be extended to aliphatic substrates with flexible structures whose hydroxyl groups are not close to the activated C—H bond (Scheme 3). For this purpose, we started our investigations with

aliphatic alcohols of different lengths ranging from 1-decanol to 1-docosanol. Gratifyingly, the same reaction procedure proved applicable to non-pre-oriented aliphatic alcohols giving the corresponding products after column chromatography on silica gel in good yields ranging from 58% to 79% (**2b**–**5b**).

The formation of the corresponding tetrahydropyran (THP)-product was not observed to the best of our knowledge, indicating that the reaction favors the formation of 5-membered cycles over 6-membered cycles. The cyclization reaction of 1-decanol was monitored by analyzing reaction aliquots *via* ^{1}H NMR spectroscopy (see ESI, Figure 1). The reaction follows second-order kinetics, and after 3 h, a steady-state is reached. When the missing amounts of PhI(*m*-CBA)$_2$

Scheme 3. Competition experiments. Conditions: PhI(mCBA)$_2$ (1.0 equiv.) 10 mol% I$_2$, 1,2-DCE, 45 °C, 500 W lamp. [a] 1.0 equiv. I$_2$.

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Figure 1. Scope of the light-induced iodine-catalyzed cyclization reaction under the presented reaction conditions: I_2 (10 mol%), PhI(m-CBA)$_2$ (1.0 equiv.), 1,2-DCE, 45 °C, 500 W halogen lamp, overnight (ca. 16 h). Yields were determined after purification by column chromatography on silica gel. The newly formed C–O bonds are highlighted in red. [a] 1.0 equiv. I_2 was used.

combined with additional 10 mol% iodine were added to achieve complete conversion, no starting material was left after another hour of irradiation at the latest. To investigate the substrate scope in more detail, branched alcohols were included in our studies, allowing different substitution patterns on the THF motif. As a consequence of the radical reaction mechanism of the cyclization, no diastereoselectivity was observed giving the 2,n-*cis*- and the 2,n-*trans*-substituted product in a 1:1 mixture (n=3: **9b**, **7b** and **8b**; n=4: **6b**) in overall good yields of about 50% for n=3 and 71% for **6b**. To access 2,5-substituted THF moieties, unbranched and branched secondary alcohols were successfully subjected to the reaction conditions building the related products as a 1:1 mixture of their *cis/trans*-isomers in yields that are comparable to 2-alkyl THFs (**11b**: 56%, **12b**: 68% and **13b**: 64%).

Activation of a benzylic position was also feasible as it was shown for **14b** (48%), whereby functional groups such as a methoxy group (**15b**: 47%) or a bromo residue (**16b**: 48%) were well tolerated at the aromatic without any impact on the yield. To further explore the tolerance towards functional groups, substituted alkyl chains were examined. We commenced with common OH-protecting groups such as alkyl-, benzyl- or silyl ether and an acetyl protecting group, all of which give the corresponding products in moderate yields (**19b**: 37% (Me), **20b**: 43% (SiR$_3$), and **21b**: 46% (Ac). When stoichiometric amounts of iodine were applied, an increase in yield was observed, as demonstrated for **21b** (75%), showing that the functional groups impact the turnover of the

cyclization. By augmenting the distance between the δ-C–H bond and the functional group, yields could be in some cases augmented as shown for **26b**: 50% (OMe) and **27b**: 62% (Ac) while the corresponding benzyl protected alcohol **28b** was obtained in similar yields of 46% (OBn). When stoichiometric amounts of I_2 were used, no significant improvements in yield were observed. In comparison, lower yields were obtained for alcohols containing a tosyl (**22b**: 34%), a cyano (**23b**: 42%), an ester (**24b**: 37%) or carboxyl group (**25b**: 31%). We were happy to see that a phthalimide containing alcohol was also well tolerated affording the THF-product **29b** in 54% yield.

A benzylic C–H-bond next to oxygen was successfully activated, giving the corresponding 1,3-dioxolane **17b** in 56% yield. When blocking the δ-position of the alcohol with an oxygen atom, as is the case for 3-(benzyloxy)propanol, the formation of the corresponding 6-membered cycles occurred, affording the 1,3-dioxane product **18c** in 67% yield.

This result motivated us to conduct competition experiments to understand better the reactivity of alcohols bearing two competing reaction sites (Scheme 3). As a result, we demonstrated that even in the presence of a more activated, benzylic C–H-bond, only the formation of the 5-membered THF ring is observed, implying the entropic control of the reaction (experiment 1; **30b**: 40%). The corresponding THP-product **30c** was not formed in detectable amounts. Furthermore, the cyclization reaction favors the activation of secondary C–H-bonds over primary C–H-bonds in aliphatic alcohols as exclusively the more electron-rich secondary C–H-bond was attacked as showcased for 4-undecanol (**31a**), giving **31b** even though only in 36% yield (experiment 2). In the absence of an aliphatic secondary C–H bond, an aromatic C–H bond is activated even if this causes the formation of the generally unfavored 6-membered THP-ring, even in the presence of a primary δ-C–H bond (experiment 3 and 4).

Noteworthy, the formation of 2,3-dihydrobenzofuran has never been observed, not even in therefore designed substrates. In the presence of an aliphatic secondary C–H bond, its activation occurs again preferentially, and the THF-products **34b** and **35b** were isolated in 37% (**34b**) and 58% yield (**35b**) (experiment 5 and 6). Again, the usage of stoichiometric amounts of I_2 showed no impact on the yield in the cyclization of **34a**. Interestingly, for the primary alcohol **36a** comprising three different potentially addressable C–H bonds, the opposite behavior was observed as chromane **36c** was detected (experiment 7). This observation was attributed to the steric demand of the residues at the C-3 hindering the attack by the hypervalent iodine reagent as both **13b** and **17b** were successfully built in good yields (Scheme 3).

Next, we investigated if 1,n-diols (n=6–12) can undergo double C–H activation and whether any trend is detectable (Figure 2). In most cases, a double C–H-activation took place, but for 1,6-hexanediol and 1,8-octanediol, we could only isolate the mono-cyclized products (see ESI), which might also be due to the high volatility of the double-cyclized products. Gratifyingly, we were able to detect **37bb** despite its low boiling point (48–52 °C/12 mmHg) when column chromatography was conducted with low-boiling solvents and if those were not
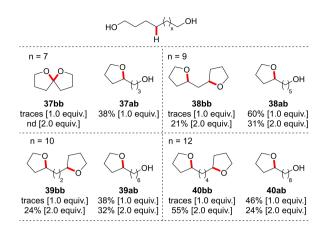
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Figure 2. Reaction of 1,n-diols (n = 6–12) under light-induced iodine-catalyzed cyclization reaction conditions: I_2 (10 mol%), PhI(m-CBA)$_2$ (1.0 or 2.0 equiv.), 1,2-DCE, 45 °C, 16 h. Yields were determined after purification by column chromatography on silica gel. The newly formed C–O bonds are highlighted in red. x = 2–7; nd = not determined. More examples (n = 6, 8) can be found in the ESI.

completely removed. However, longer 1,n-diols (n ≥ 9) were transformed in good yields to their double-cyclized products (**38bb**: 24%, **39bb**: 24%, **40bb**: 55%) in the presence of 2.0 equiv. of oxidant and 20 mol% iodine whereby these were accompanied by their mono-cyclized products (**38ab**: 31%, **39ab**: 31%, **40ab**: 24%). Almost no double activation was observed, with only one equivalent of oxidant showing that the first cyclization is preferred over the second C–H activation.

Finally, the developed cyclization reaction was applied to additional steroidal substrates showing that both the C–H-bond of the C-19 and the C-18 methyl group can be addressed (Figure 3). This observation was showcased for the highly functionalized corticosterone 21-acetate giving the corresponding product **41b** in good yields of 47%. We were more than pleased to functionalize a tertiary C–H-bond of the pregnene-derivative by taking advantage of the proximity of the produced oxygen radical at C-18 and the tertiary 20-C–H bond showing that also tertiary C–H groups are accessible. Noteworthy, the yield could not be improved by using higher amounts of iodine and/or oxidant – on the contrary, the product could not be isolated anymore.

When subjecting (+)-menthol (**43a**) to the developed reaction conditions, activation of a primary C–H bond took place, affording the corresponding diastereomeric products
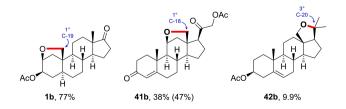

Figure 4. Derivatization of (+)-menthol (**43a**).

43b in a 3:1 mixture in 38% total yield (Figure 4). These results support that oxidization of the primary C–H bond is feasible if the hydroxyl group and the methyl group are in close proximity.

We have presented the first iodine-catalyzed synthesis for different substituted tetrahydrofurans through an intramolecular C(sp³)–H oxidation of non-activated remote C(sp³)–H bonds. The reaction proceeds under high regioselectivity favoring the formation of the 5-membered rings over the thermodynamically more stable 6-membered rings. This method requires only a single equivalent of oxidant per activated C–H bond, is operationally simple, and can be initiated either by daylight or a simple halogen lamp. The proposed reaction mechanism is based on two intertwined catalytic cycles combining a radical chain reaction with an iodine(I/III) redox couple. Although involving radicals, the reaction proceeds under mild conditions and is therefore of a broad substrate scope tolerating multiple functional groups that also allow further derivatization of the constructed THF-containing products. Aliphatic primary and secondary alcohols can be cyclized and aliphatic 1,n-diols giving access to molecules with one or two THF moieties. The disclosed method demonstrates the potential of iodine catalysis as a non-toxic and powerful alternative for the conventional metal-catalyzed synthesis of tetrahydrofurans.[19]

Conflict of Interest

The authors declare no conflict of interest.

Figure 3. Exploitation of the substrate scope towards steroids based on the frameworks of androsterone (**1b**), corticosterone (**41b**), and pregnenolone (**42b**).

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[19] An alternative in some cases is the use of ultra-sound irradiation. These protocols are currently under investigation. S. Al Muthafer, A. Winter, S. Marschner, V. Koch, S. Bräse, unpublished.