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Diastereoselective Formation of Anellated Tetrahydrofurans Using a Nitrate Radical Induced Oxidative, Self-Terminating Radical Cyclization Cascade[#]

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Abstract: Addition of electrogenerated nitrate radicals to C≡C triple bonds in the alkynyl ethers *cis*-**7-9** and *trans*-**8-9** yields anellated tetrahydrofurans **12-16** with high diasteroselectivity through a new type of an oxidative, self-terminating radical cyclization cascade. The reaction probably proceeds via an intramolecular, rate-determining hydrogen atom transfer in the vinyl radical of type **17a**, and a subsequent diastereoselective 5-*exo* radical cyclization. Elimination of nitrogen dioxide terminates the reaction sequence. This reaction is a remarkable example for the creation of a C-O bond by intermolecular addition of an O-centered radical to a π-system.
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Keywords: Radicals and radical reactions; Diastereoselection; Bicyclic aliphatic compounds.

Introduction

In contrast to the intramolecular processes, formation of C-O bonds by intermolecular addition of O-centered radicals to π-systems is not well established yet. This is due to the fact that organic radicals of the type RO• react preferentially through β-fragmentation and hydrogen atom abstraction, especially from an allylic position, than by addition.[2] The inorganic O-centered nitrate radical (NO_3•) plays a major role as nighttime oxidant in the earth's atmosphere. The initial reactions steps in the interactions with organic compounds can be hydrogen atom abstraction, addition to π-systems, and electron transfer in the case of easily oxidizible compounds. Though numerous investigations were carried out to understand the role of NO_3• in the atmospheric transformations,[3-5] this radical is comparatively unknown in organic synthesis.[6-8] It is our intention to demonstrate that NO_3• is a versatile oxidizing reagent which can be applied to fields in radical chemistry which are not well accessible with organic radicals due to energetically unfavorable interactions between the SOMO and the relevant orbital of the π-system,[9] and side reactions (see above): (i) intermolecular radical addition to C≡C triple bonds, and (ii) formation of a C-O bond by such an addition process.

Recently, we described a transannular, oxidative radical cyclization cascade induced by addition of the electrophilic NO_3• to C≡C triple bonds in medium-sized cycloalkynes **4** and cycloalkynones **5**.[1] Bicyclic ketones and α,β-epoxy ketones, respectively, were formed after transannular participation of a methylene unit (in **4**) or the carbonyl group (in **5**) in good to high yields, depending on the ring size of the substrate. The role of NO_3• in this sequence may be that of a donor of atomic oxygen, the latter can be generated in solution only with difficulty. This result encouraged us to apply this radical cyclization also to the synthesis of ring compounds by NO_3• addition to the C≡C triple bond in open chain alkynes.

Attempts to cyclize the linear alkynes and alkynones **1a-d** by NO_3• addition to the triple bond were unsuccessful. This may be due to side reactions (presumably hydrogen atom abstraction from the solvent) in the intermediately formed vinyl radicals **2a-d** and **3a-d**, respectively, which were faster than bond rotations to yield

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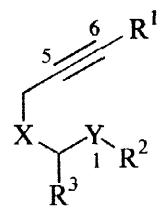
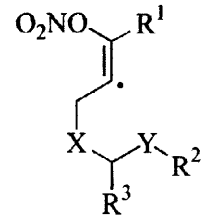
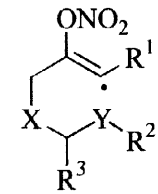
conformations, in which the unpaired electron and the hydrogen atom donor (Y : CH_2) or the radical acceptor (Y : C=O), respectively, could approach.



1a-d



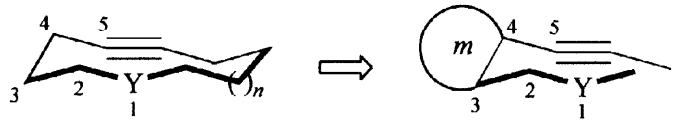
2a-d



3a-d

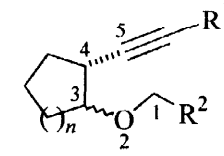
1,2,3	X	Y	R^1	R^2	R^3
a	CH_2	CH_2	H	Me	H
b	CMe_2	C=O	H	Me	H
c	CMe_2	C=O	Me	Me	H
d	O	C=O	Me	$-(CH_2)_4-$	

A simulation of the conformation in medium-sized rings, in which intramolecular reactions are entropically favored with respect to intermolecular processes, could be achieved by introducing a cycloalkyl clamp into a linear alkyne. This should reduce the rotational degrees of freedom in the molecule, as shown in **6**, and lead to the design of the 3,4-cycloalkyl fused alkynyl ethers *cis/trans*-**7-9** as suitable compounds.



4: Y = CH_2
5: Y = C=O

6
3,4-fusion



cis/trans-	*n*	R^1	R^2
7	1	*n*-Bu	Me, Et*, OMe*, CN*
8	2	Me, *n*-Bu	Me, Et
9	3	*n*-Bu	Et

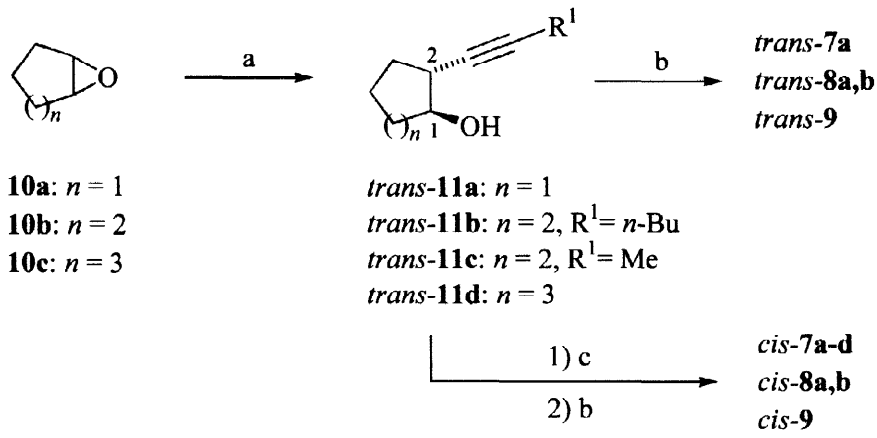
* Only *cis*.

$NO_3^•$ was generated by anodic oxidation of lithium nitrate[6-8,10,11] in a solvent mixture of acetonitrile/water/diethyl ether (5:1:2).[1] In a typical experiment the alkyne and 2.5 equivalents of nitrate were electrolyzed in an undivided cell until complete consumption of the alkyne. This electrochemical method allows a reagent-free radical generation, which is an important point, as the demands for non-toxic alternatives in radical chemistry have continually increased during recent years.[12]

Results

cis/trans-**7-9** were available in good yields according to the procedure outlined in Scheme 1. Opening of the epoxides **10a-c**[13] with an acetylide using the method of Barks et al.[14] leads to the *trans*-configurated alcohols

trans-**11a-d** which were then alkylated to give the ethers *trans*-**7-9**. The respective *cis* ethers *cis*-**7-9** were obtained by Mitsunobu inversion[15] of the stereogenic center C-1 in *trans*-**11a-d** and subsequent alkylation of the resulting alcohols *cis*-**11a-d** (not shown). The cyanomethoxy compound *cis*-**7d** was prepared according to Corey et al.[16,17] by first converting the alcohol *cis*-**11b** into a methoxyethoxymethyl ether which was then treated with diethylaluminium cyanide to give *cis*-**7d** (see Experimental).



a: ≡–R^1, *n*-BuLi, BF_3·Et_2O, 66-98%; b: R^2CH_2X, base, 58-94%; c: 1. EtOC(O)N=NC(O)OEt, PhCOOH, PPh_3; 2. NaOMe, MeOH; 43-47%.

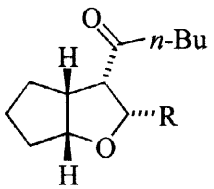
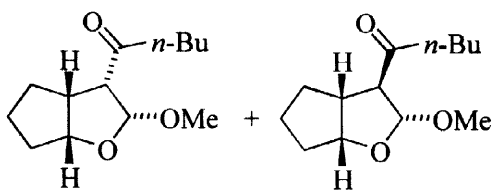
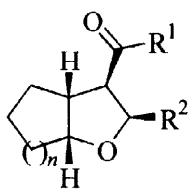
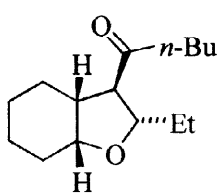
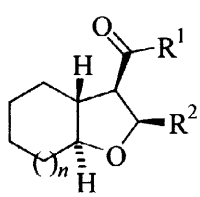
Scheme 1

By reacting the alkynyl ethers *cis*-**7-9** and *trans*-**8-9** with NO_3 radicals anellated tetrahydrofurans **12-16** with four stereogenic centers were obtained (Table 1). With exception of the methoxy substituted alkynyl ether *cis*-**7c** the reaction was highly diastereoselective leading to only one single diastereoisomer. The stereochemistry in the reaction products **12-16** was determined by ^1H NMR from coupling constants and NOE measurements. In addition, in some cases the distances between the hydrogen atoms at the tetrahydrofuran ring were calculated from the NOE integrals and compared with distance values, which were obtained from force field calculations of different diastereoisomers.

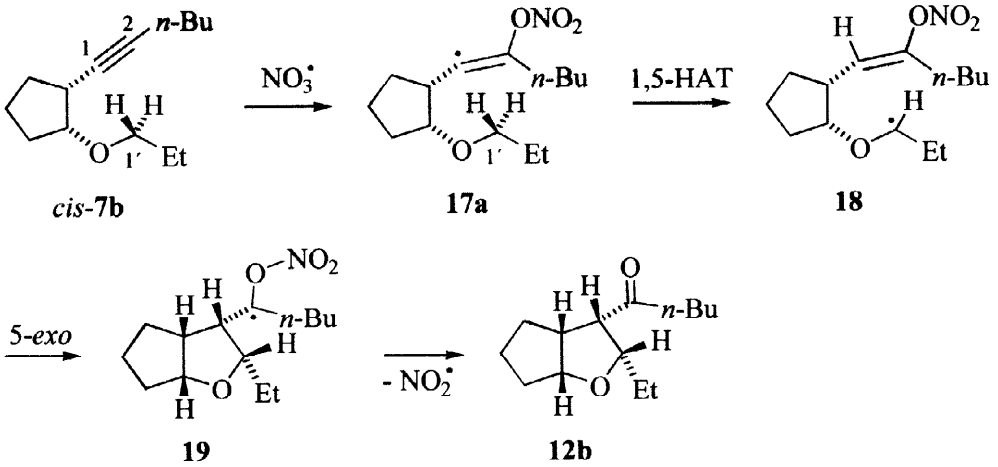
A possible reaction pathway leading to the cyclized products is exemplary shown for the reaction of *cis*-**7b** in Scheme 2. $NO_3^\bullet$ may add to the less hindered site of the C≡C triple bond (C-2) to form the vinyl radical **17a**. An intramolecular 1,5-hydrogen atom transfer (HAT) from C-1′ yields the radical **18** which is stabilized by the adjacent oxygen atom. Subsequent 5-*exo* radical cyclization to the new formed C=C double bond to give **19** and finally loss of nitrogen dioxide ($NO_2^\bullet$) leads to the tetrahydrofuran **12b**.

Formation of a stable C=O π-bond and the increasing entropy through fragmentation of radical **19** in the termination step is expected to be the driving force in this radical cyclization. This reaction sequence may therefore be regarded as *oxidative*, *self-terminating* radical cyclization as by intermolecular addition of $NO_3^\bullet$ to the alkyne a cyclization cascade is induced, which is terminated through a unimolecular decomposition step in radical **19**. The released $NO_2^\bullet$ is comparatively unreactive with respect to $NO_3^\bullet$, the latter being, in addition, the excess component in the whole reaction system. Products resulting from side reactions involving $NO_2^\bullet$ were not found yet.

Table 1: Results of the reaction of $NO_3^\bullet$ with the alkynyl ethers *cis/trans*-**7-9**. Isolated yields are given.

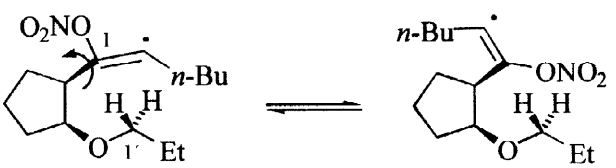
Alkynyl Ether	Product	Yield
cis-**7a**: R^1 = *n*-Bu, R^2 = Me *cis*-**7b**: R^1 = *n*-Bu, R^2 = Et	 **12a**: R = Me **12b**: R = Et	**12a**: 25% **12b**: 35% (45%) [a]
cis-**7c**: R^1 = *n*-Bu, R^2 = OMe	 **13a** + **13b**	28% **13a** : **13b** = 2.4 : 1 [b]
cis-**7d**: R^1 = *n*-Bu, R^2 = CN *cis*-**8b**: R^1 = R^2 = Me *cis*-**9**: R^1 = *n*-Bu, R^2 = Et	 **14a**: *n* = 1, R^1 = *n*-Bu, R^2 = CN **14b**: *n* = 2, R^1 = R^2 = Me **14c**: *n* = 3, R^1 = *n*-Bu, R^2 = Et	**14a**: 21% **14b**: 9% **14c**: 17%
cis-**8a**: R^1 = *n*-Bu, R^2 = Et	 **15**	11%
trans-**7a**: R^1 = *n*-Bu, R^2 = Me	no cyclized product	
trans-**8a**: R^1 = *n*-Bu, R^2 = Et *trans*-**8b**: R^1 = R^2 = Me *trans*-**9**: R^1 = *n*-Bu, R^2 = Et	 **16a**: *n* = 1, R^1 = *n*-Bu, R^2 = Et **16b**: *n* = 1, R^1 = R^2 = Me **16c**: *n* = 2, R^1 = *n*-Bu, R^2 = Et	**16a**: 34% **16b**: 27% **16c**: 16%

[a] Yield obtained in acetonitrile/water/*tert*-butyl methyl ether (5:1:2). – [b] Products not separated. The stereochemistry was determined from chemical shifts and coupling constants in the proton NMR spectrum of the product mixture.



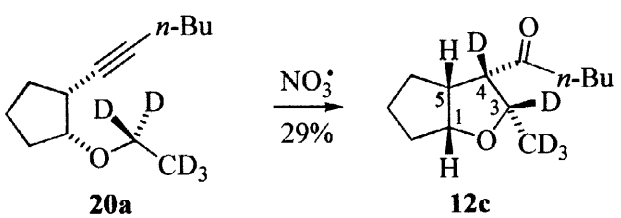
Scheme 2

The regiochemistry of the initial intermolecular radical addition to π-systems is generally dependent on both, steric and electronic factors.[9] Since in *cis*-**7b** and its homologues both sites of the alkyne bond were equally substituted by alkyl groups, the electronic factor should be unimportant in this radical addition step. Though the steric hindrance at C-1 should be significantly higher with respect to that at C-2, $NO_3^•$ attack at C-1 could not be excluded. However, in contrast to **17a**, the resulting vinyl radical **17b** possesses rotational degrees of freedom which lead to low-energy conformers, in which an intramolecular HAT is not possible.

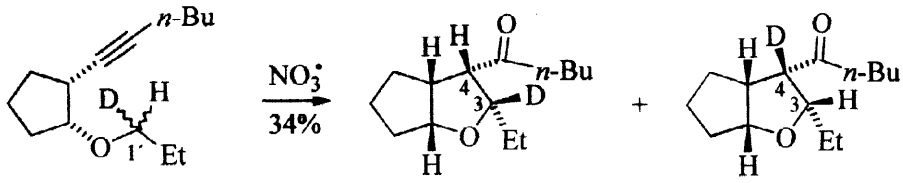


17b

The intramolecular nature of the 1,5-HAT was verified by reacting the polydeuterated alkynyl ether **20a** with $NO_3^•$. No proton signal at C-4 in the reaction product **12c** was observed by ^1H NMR spectroscopy.



With the monodeuterated compound **20b** a primary kinetic isotope effect $k_H/k_D = 3$ for the 1,5-HAT was determined from the ^1H NMR spectrum of the isomeric mixture of the cyclized products **12d** and **12e**. This value indicated not only that the HAT step was rate determining but also supported the assumed reaction pathway outlined in Scheme 2. Since **20b** was not prepared enantiomerically pure but used as a 1:1 diastereomeric mixture, these data did not enable us to localize the transition state of the HAT on the hyperpotential surface.



20b
1:1 mixture of diastereoisomers

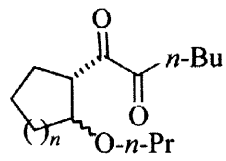
12d : **12e** = 3 : 1
$k_H/k_D = 3$

12d

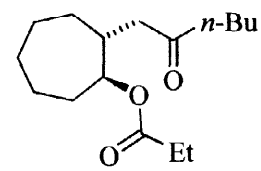
12e

The stereochemistry of the two newly formed stereogenic centers in the reaction products **12-16** was determined in the 5-*exo* radical cyclization step (see Scheme 2) and was dependent on both, size of the anellating ring and stereochemistry of the attached substituents as well as on the electronic properties of R^2. A detailed discussion concerning the transition states in these radical cyclizations will be given elsewhere.[18]

Besides the tetrahydrofurans, also 1,2-diketones *cis/trans*-**21** and the ketoester **22** were formed in these reactions as by-products in low yields. These compounds were presumably formed by either anodic or NO_3• induced oxidation of the intermediate radicals **17a** or **18**, respectively, trapping the resulting cations by addition of water from the solvent mixture and subsequent hydrolysis and oxidation steps.

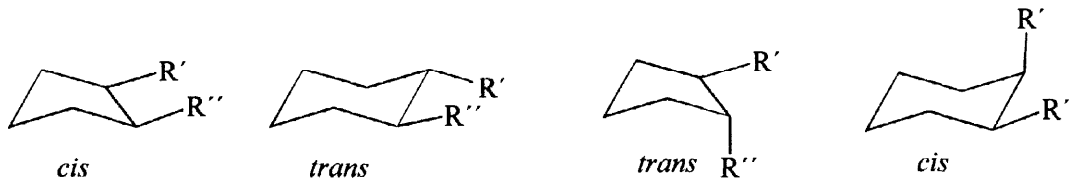


cis-**21a**: $n = 1$ (5%)
trans-**21b**: $n = 2$ (10%)
trans-**21c**: $n = 3$ (5%)



22 (2%)

Semiempirical calculations[19] predicted that the yields of cyclized products should be dependent on both size of the connecting ring and stereochemistry of the ring substitution. The experiments were in accordance with these predictions and had shown that reasonable yields were obtained in those systems in which both substituents R′ and R″ were approximately lying in a plane, i.e. in the *cis* disubstituted cyclopentyl derivatives *cis*-**7a-d** and the *trans* disubstituted cyclohexyl systems *trans*-**8a-b**, respectively. In *trans*-**7a** both substituents pointed in nearly orthogonal directions. Therefore, any cyclization was prevented because the reaction centers could not approach during the lifetime of the respective intermediate vinyl radical of type **17a** (see Scheme 2). The low yield in the reaction of *cis*-**8a-b** with NO_3• was also due to a poor interaction between the alkynyl and the ether substituent. The increased flexibility of the cycloheptyl ring reduced the differences between *cis* and *trans* disubstitution and the yields obtained by reacting *cis*-**9a** and *trans*-**9a**, respectively, with NO_3• were comparable.



Generally, the yields of cyclization products were not very high yet. This may be due to fast side reactions of the reactive vinyl radical intermediates of type **17a**. Intermolecular hydrogen atom abstraction by **17a** would be expected to be the most important parallel reaction but this reaction was not further investigated. A potential source for hydrogen atoms may be diethyl ether from the solvent mixture.[20] First attempts to replace diethyl

ether by *tert*-butyl methyl ether, which is just as polar but without easily abstractable hydrogen atoms, already lead to an increase in product yield (see Table 1). Experiments to further improve the yields by varying the reaction conditions are underway.

Anyway, the value of this self-terminating, oxidative radical cyclization should be stressed with these results already. Using this method, highly substituted, functionalized tetrahydrofurans, which are substructures in many naturally occurring compounds, can be synthesized with excellent diastereoselectivity in one single cyclization step from starting materials, which themselves are available in high yields from omnipresent chemicals in a short reaction sequence.

Experimental

IR data were measured on a Perkin-Elmer FTIR spectrometer 1600. ^{1}H NMR spectra were recorded on Bruker AM 300 and DRX 500 operating at 300 or 500 MHz, respectively. ^{13}C NMR spectra were obtained on the same instruments operating at 75.5 or 125.8 MHz, respectively. Chemical shifts in $CDCl_3$ are quoted relative to TMS for ^{1}H NMR (δ = 0.0 ppm) and relative to the solvent for ^{13}C NMR (δ = 77.0 ppm for ^{13}C of $CDCl_3$). Stars (*) indicate that the assignment may be exchanged. Mass spectra were recorded on a Finnigan MAT 8200 instrument at 70 eV ionizing potential, isobutane was used for chemical ionization (CI). Elemental analyses were performed by the *Mikroanalytisches Laboratorium Ilse Beetz*, Kronach, Germany. The chemicals and solvents were purified using standard procedures.

Electrolysis experiments were performed in an undivided cell (50 or 100 ml beaker) equipped with a cylindrical platin net anode and a centered platin or stainless steel cathode. A silver/silver chloride/(0.1M tetraethylammonium chloride in acetonitrile) electrode ($E_0 \approx$ SCE) was used as reference. The electrolysis were carried out at potentials of U = 2.0-2.4 V and currents of I = 200 ± 30 mA under magnetic strirring and cooling by means of a water bath.

Synthesis of the starting materials, general procedure: The alcohols *trans*-**11a-d** were synthesized from the respective epoxides **10a-c**[13] according to Barks et al.[14]

Alkylation of the alcohols *cis/trans*-**11**[14,18] : Pulverized potassium hydroxide (5.2 eq.) was suspended in DMSO (1 mL/mmol) and stirred 10 min under argon at room temperature (rt). To this mixture a solution of the alcohol *cis/trans*-**11** in DMSO (1 mL/mmol) and the alkylating reagent (methyl iodide, ethyl bromide, propyl bromide, 12.5 eq) were added and stirred at rt over night. The ice-cooled mixture was carefully hydrolyzed with water and extracted several times with ether. The combined organic fractions were dried, evaporated and purified by column chromatography (SiO_2). Due to the extremely high volatility of the 3,4-cycloalkyl fused alkynyl ethers *cis/trans*-**7-9** elemental analyses could not be performed.

Mitsunobu inversion: *trans*-**11**, Triphenylphosphine (2 eq.) and benzoic acid (2 eq.) were dissolved under argon in abs. THF (3 mL/mmol). Diethyl azodicarboxylate (2 eq.) was added at <30°C and the mixture stirred at rt over night. The solvent was evaporated, the residue dissolved in diethyl ether and stirred at rt until a white precipitate was formed. The solid was separated by filtration, the filtrate reduced in vacuo and the residue purified by column chromatography (SiO_2, *n*-pentane/diethyl ether). The isolated benzoic ester was then dissolved in methanol (7 mL/mmol), and sodium methylate (6 eq.) was added under cooling and the mixture stirred 24 h at rt. After evaporation of the solvent the residue was dissolved with water, acidified with diluted hydrochloric acid and extracted with dichloromethane. After drying of the combined organic fractions the inverted alcohols *cis*-**11** were isolated by column chromatography (SiO_2, *n*-pentane/diethyl ether).

(±)-*trans*-Ethoxy-2-(hex-1-ynyl)-cyclopentane (*trans*-7a)

Yield: 81%, colorless liquid. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.26. – IR (film): $\tilde{\nu}$ = 2959, 2931, 2872 (ν C-H); 1444, 1370, 1345 (δ C-H); 1119, 1092 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 3.82 (1H, dt, J = 4.4, 6.7 Hz, 1-H), 3.60 (1H, dq, J = 7.0, 9.4 Hz, 1′′-H_A), 3.49 (1H, dq, J = 7.0, 9.4 Hz, 1′′-H_B), 2.62 (1H, m), 2.15 (2H, dt, J = 2.3, 4.6 Hz), 1.99 (1H, m), 1.93 (1H, ddd, J = 6.7, 6.7, 8.5 Hz, 2-H), 1.71 - 1.65 (2H, m), 1.63 - 1.55 (2H, m), 1.49 - 1.35 (4H, m), 1.19 (3H, t, J = 7.0 Hz, 2′′-H_2), 0.90 ppm (3H, t, J = 7.3 Hz, 6′-H_2). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 86.7 (d, C-1), 82.7 (s, C-1′)*, 81.1 (s, C-2′)*, 64.6 (t, C-1′), 36.7 (d, C-2), 32.1 (t), 31.8 (t), 31.1 (t), 22.6 (t), 21.9 (t), 18.5 (t, C-3′), 15.5 (q, C-2′′), 13.6 (q, C-6′). – MS (CI); *m/z* (%): 195 (4) [M^++H], 149 (100).

(±)-*cis*-Ethoxy-2-(hex-1-ynyl)-cyclopentane (*cis*-7a)

Yield: 93%, colorless liquid. – R_f [*n*-pentane/diethyl ether 40:1)] = 0.21. – IR (film): $\tilde{\nu}$ = 2959, 2931, 2871 (ν C-H); 1450 (δ C-H); 1124 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 3.78 (1H, ddd, J = 5.4, 5.4, 5.4 Hz, 1-H), 3.69 (1H, qd, J = 7.0, 9.2 Hz, 1′′-H_A), 3.52 (1H, qd, J = 7.0, 9.2 Hz, 1′′-H_B), 2.70 (1H, tdt, J = 2.3, 5.2, 7.0 Hz, 2-H), 2.19 (2H, dt, J = 2.3, 7.0 Hz, 3′-H_2), 1.86 - 1.70 (5H, m, 3-H_2, 4-H_A, 5-H_2), 1.54 - 1.38 (5H, m, 4-H_B, 4′-H_2, 5′-H_2), 1.21 (3H, t, J = 7.0 Hz, 2′-H_3), 0.90 ppm (3H, t, J = 7.3 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 82.2 (s, C-2′)*, 81.8 (d, C-1), 79.7 (s, C-1′)*, 65.1 (t, C-1′′), 35.3 (d, C-2), 31.1 (t), 30.9 (t), 30.8 (t), 21.8 (t), 21.3 (t), 18.6 (t, C-3′), 15.3 (q, C-2′′), 13.6 ppm (q, C-1′). – MS (70 eV); *m/z* (%) = 194 (5) [M^+], 179 (6), 165 (13), 137 (75).

(±)-*cis*-Propoxy-2-(hex-1-ynyl)-cyclopentane (*cis*-7b)

Yield: 85%, colorless liquid. – R_f [*n*-pentane/diethyl ether (40:1)] = 0.25. – IR (film): $\tilde{\nu}$ = 2958, 2932, 2872 (ν C-H); 1465 (δ C-H); 1121, 1097 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 3.76 (1H, ddd, J = 5.2, 5.2, 5.2 Hz, 1-H), 3.57 (1H, td, J = 6.8, 9.2 Hz, 1′′-H_A), 3.41 (1H, td, J = 6.7, 9.2 Hz, 1′′-H_B), 2.69 (1H, tdt, J = 2.3, 5.2, 7.2 Hz, 2-H), 2.19 (2H, dt, J = 2.3, 6.9 Hz, 3′-H_2), 1.90 - 1.72 (5H, m, 3-H_2, 4-H_A, 5-H_2), 1.59 - 1.53 (2H, m, 2′′-H_2), 1.52 - 1.35 (5H, m, 4-H_B, 4′-H_2, 5′-H_2), 0.93 (3H, t, J = 7.4 Hz, 3′′-H_3), 0.90 ppm (3H, t, J = 6.4 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 82.2 (s, C-1′)*, 82.0 (d, C-1), 79.8 (s, C-2′)*, 71.5 (t, C-1′′), 35.4 (d, C-2), 31.2 (t), 30.9 (t), 30.8 (t), 23.1 (t), 21.9 (t), 21.3 (t), 18.6 (t), 13.6 (q, C-6′), 10.6 ppm (q, C-3′′). – MS (CI); *m/z* (%) = 209 (6) [M^++H].

(±)-*cis*-Methoxymethoxy-2-(hex-1-ynyl)-cyclopentane (*cis*-7c)

1.64 g (9.88 mmol) *cis*-**11a** were dissolved in 80 mL abs. dichloromethane, and 13.6 mL (79.44 mmol) diisopropylethyl amine and a small amount of dimethylamino pyridine were added. After cooling to 0°C, 3.0 mL (39.50 mmol) methoxymethyl chloride were added dropwise. The mixture was stirred for 2 h at 0°C and 48 h at rt. The solution was diluted with 100 mL dichloromethane and washed with 30 mL 0.5N hydrochloric acid and with 40 mL brine. The aqueous phases were extracted with 30 mL dichloromethane, the combined organic fractions were dried and concentrated in vacuo. After column chromatography [SiO_2, *n*-pentane/diethyl ether (15:1)], 1.82 g (8.67 mmol, 88%, R_f = 0.22) *cis*-**7c** were obtained as a colorless liquid.

IR (film): $\tilde{\nu}$ = 2956, 2932, 2874 (ν C-H); 1466 (δ C-H); 1146, 1102, 1049 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 4.80 (1H, d, J = 6.8 Hz, 1′′-H_A), 4.69 (1H, d, J = 6.8 Hz, 1′′-H_B), 4.09 (1H, ddd, J = 3.7, 4.8, 4.8 Hz, 1-H), 3.41 (3H, s, OCH_3), 2.65 (1H, m, 2-H), 2.19 (2H, dt, J = 2.3, 7.0 Hz, 3′-H_2), 1.94 - 1.75 (5H, m, 3-H_2, 4-H_A, 5-H_2), 1.62 - 1.33 (5H, m, 4-H_B, 4′-H_2, 5′-H_2), 0.88 ppm (3H, t, J = 7.2 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 95.3 (t, C-1′′), 82.3 (s, C-1′)*, 79.7 (s, C-2′)*, 79.1 (d, C-1), 55.3 (q, OCH_3),

36.1 (d, C-2), 31.2 (t), 31.1 (t), 30.8 (t), 22.0 (t), 21.5 (t), 18.6 (t, C-3′), 13.6 ppm (q, C-6′). – MS (CI); *m/z* (%) = 211 (8) [M^++H], 195 (24), 181 (57), 179 (100), 177 (14), 153 (9).

(±)-*cis*-Cyanomethoxy-2-(hex-1-ynyl)-cyclopentane (*cis*-7d)

a) (±)-cis-2-(Hex-1-ynyl)-cyclopentylmethoxyethoxymethyl ether: To a solution of 913 mg (5.50 mmol) *cis*-**11a** were added at 0°C unter nitrogen 3.4 mL (5.50 mmol) *n*-butyl lithium (1.6N in *n*-hexane) and stirred for 30 min. 1.1 mL (9.71 mmol) 2-methoxyethoxymethyl chloride were added and the reaction mixture stirred in an ice bath over night. The solution was poured into brine and extracted with diethyl ether. After drying and evaporation of the solvent the residue was purified by column chromatography [SiO_2, *n*-pentane/diethyl ether (5:1)] to give 1.22 g (4.78 mmol, 87%, R_f = 0.18) of the desired ether as a colorless liquid.

IR (film): $\tilde{\nu}$ = 2959, 2932, 2873 (ν C-H); 1452 (δ C-H); 1097, 1051 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 4.89 (1H, d, J = 7.0 Hz, OCH_AH_BO), 4.73 (1H, d, J = 7.0 Hz, OCH_AH_BO), 4.12 (1H, ddd, J = 4.6, 4.6, 4.6 Hz, 1-H), 3.81 (1H, ddd, J = 3.6, 5.8, 11.00 Hz, $OCH_AH_BCH_2OCH_3$), 3.73 (1H, ddd, J = 3.8, 5.7, 11.00 Hz, $OCH_AH_BCH_2OCH_3$), 3.59 (1H, ddd, J = 3.6, 5.7, 10.7 Hz, $OCH_2CH_AH_BOCH_3$), 3.59 (1H, ddd, J = 3.8, 5.7, 10.7 Hz, $OCH_2CH_AH_BOCH_3$), 3.40 (3H, s, OCH_3), 2.66 (1H, tdt, J = 2.3, 5.1, 8.6 Hz, 2-H), 2.17 (2H, dt, J = 2.3, 7.0 Hz, 3′-H_2), 1.91 (1H, m, 3-H_A), 1.85 - 1.74 (4H, m, 3-H_B, 4-H_A, 5-H_2), 1.56 (1H, m, 4-H_B), 1.49 - 1.36 (4H, m, 4′-H_2, 5′-H_2), 0.90 ppm (3H, t, J = 7.3 Hz, 3H, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 94.3 (t, OCH_2O), 82.3 (s, C-2′)*, 79.7 (s, C-1′)*, 79.2 (d, C-1), 71.6 (t, $OCH_2CH_2OCH_3$), 66.7 (t, $OCH_2CH_2OCH_3$), 59.0 (q, OCH_3), 36.1 (d, C-2), 31.2 (t, C-4′), 31.0 (t, C-5), 30.8 (t, C-4), 22.0 (t, C-5′), 21.4 (t, C-3), 18.6 (t, C-3′), 13.7 ppm (q, C-6′). – MS (CI); *m/z* (%) = 255 (4) [M^++H], 179 (100).

b) (±)-cis-Cyanomethoxy-2-(hex-1-ynyl)-cyclopentane (cis-7d): Under nitrogen 970 mg (3.82 mmol) of the ether prepared under a) and 21.0 mL (21.00 mmol) diethylaluminium cyanide (1M in toluol) were heated to 100°C for 3 h after which additional 10.0 mL (10.00 mmol) of cyanide were added and the mixture again heated for 60 min. After cooling 80 ml of a satd. aqueous solution of potassium sodiumtartrate were added, stirred for 30 min and diluted with 400 mL diethyl ether. Additional 80 mL of tartrate were added and both phases were mixed. After the aqueous phase had cleared up, the phases were separated, the aqueous phase extracted with diethyl ether, and the combined organic fractions were washed with water. Drying, evaporation of the solvent and column chromatography of the residue [SiO_2, *n*-pentane/diethyl ether 3:1)] afforded 477 mg (2.33 mmol, 61%, R_f = 0.66) *cis*-**7d** as a colorless liquid.

IR (film): $\tilde{\nu}$ = 2958, 2932 (ν C-H); 1449 (δ C-H); 1103 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 4.49 (1H, d, J = 16.2 Hz, 1′′-H_A), 4.41 (1H, d, J = 16.2 Hz, 1′′-H_B), 4.03 (1H, m, 1-H), 2.69 (1H, m, 2-H), 2.19 (2H, dt, J = 2.3, 7.0 Hz, 3′-H_2), 1.95 - 1.71 (5H, m, 3-H_2, 4-H_A, 5-H_2), 1.63 - 1.34 (5H, m, 4-H_B, 4′-H_2, 5′-H_2), 0.91 ppm (3H, t, J = 7.3 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 116.6 (s, C-2′′), 83.4 (s, C-1′)*, 83.0 (d, C-1), 78.6 (s, C-2′)*, 55.2 (t, C-1′′), 35.7 (d, C-2), 31.1 (t), 31.0 (t), 30.9 (t), 22.0 (t), 21.6 (t), 18.6 (t, C-3′), 13.6 ppm (q, C-6′). – MS (70 eV); *m/z* (%) = 205 (13) [M^+], 195 (24), 176 (6), 165 (7), 162 (6), 149 (5), 148 (9), 124 (8).

(±)-*cis*-[1,2-D_5]Ethoxy-2-(hex-1-ynyl)-cyclopentane (20a)

Under nitrogen 830 mg (5.00 mmol) *cis*-**11a** in 15 mL abs. dimethyl formamide were added to a suspension of 360 mg (15.0 mmol) sodium hydride (60% suspension in mineral oil) in dimethyl formamide at 0°C. After stirring for 15 min. 184 mg (0.50 mmol) tetrabutylammonium iodide and 2.00 g (17.54 mmol) [1,2-D_5]ethyl bromide[21] were added, the solution stirred 4 h at rt and then cooled to 0°C. The reaction was quenched by careful addition of water, diluted with 150 mL water and extracted with diethyl ether. The combined organic fractions were dried, reduced and filtrated over SiO_2 with *n*-pentane/diethyl ether (5:1). The residue was then

purified by chromatography [SiO_2, *n*-pentane/diethyl ether (40:1)] to yield 825 mg (4.15 mmol, 83%, R_f = 0.26) **20a** as a colorless liquid.

IR (film): $\tilde{\nu}$ = 2959, 2931, 2871 (ν C-H); 1450 (δ C-H); 1124 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 3.78 (1H, ddd, J = 5.3, 5.3, 5.3 Hz, 1-H), 2.69 (1H, m, 2-H), 2.18 (2H, dt, J = 2.3, 7.0 Hz, 3′-H_2), 1.90 - 1.65 (5H, m, 3-H_2, 4-H_A, 5-H_2), 1.55 - 1.38 (5H, m, 4-H_B, 4′-H_2, 5′-H_2), 0.90 ppm (3H, t, J = 7.2 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 82.3 (s, C-2′)*, 81.9 (d, C-1), 79.9 (s, C-1′)*, 65.9 (t, C-1′′), 35.4 (d, C-2), 32.0 (t), 31.2 (t), 31.0 (t), 21.9 (t), 21.4 (t), 18.7 (t, C-3′), 15.3 (t), 13.7 ppm (q, C-6′). – MS (70 eV); *m/z* (%) = 199 (4) [M^+], 181 (4), 170 (13) 165 (5) 156 (20), 149 (10), 142 (46).

(±)-*cis*-[1-D_1]Propoxy-2-(hex-1-ynyl)-cyclopentane (20b)

The preparation of **20b** was performed with 835 mg (5.03 mmol) *cis*-**11a**, 385 mg (16.04 mmol) sodium hydride, 188 mg (0.51 mmol) tetrabutylammonium iodide and 1.6 mL (17.59 mmol) [1-D_1]propyl bromide[22] as described for the synthesis of **20a**.

Yield: 907 mg (4.34 mmol, 86%), colorless liquid. – R_f [*n*-pentane/diethyl ether (7:1)] = 0.53. – ^1H NMR ($CDCl_3$, 300 MHz): δ = 3.76 (1H, ddd, J = 5.2, 5.2, 5.2 Hz, 1-H), 3.55 ($^1/_2$H, tt, J = 1.3, 6.8 Hz, 1′′-H_A), 3.39 ($^1/_2$H, tt, J = 1.3, 6.7 Hz, 1′′-H_B), 2.68 (1H, tdt, J = 2.3, 5.1, 7.4 Hz, 2-H), 2.18 (2H, dt, J = 2.3, 6.9 Hz, 3′-H_2), 1.89 - 1.72 (5H, m, 3-H_2, 4-H_A, 5-H_2), 1.65 - 1.35 (7H, m, 4-H_B, 2′′-H_2, 4′-H_2, 5′-H_2), 0.99 (3H, t, J = 7.4 Hz, 3′′-H_3), 0.90 ppm (3H, t, J = 7.2 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 82.2 (s, C-1′)*, 82.1 (d, C-1), 79.9 (s, C-2′)*, 71.5 - 70.9 (dm, C-1′′), 35.5 (d, C-2), 31.2 (t), 31.0 (t), 30.9 (t), 23.1 (t), 22.0 (t), 21.4 (t), 18.7 (t, C-3′), 13.7 (q, C-6′), 10.7 ppm (q, C-3′′). – MS (CI); *m/z* (%) = 210 (29) [M^++H], 149 (100).

(±)-*trans*-Propoxy-2-(hex-1-ynyl)-cyclohexane (*trans*-8a)

Yield: 94%, colorless liquid. – R_f [*n*-pentane/diethyl ether (30:1)] = 0.25. – IR (film): $\tilde{\nu}$ = 2958, 2932, 2858 (ν C-H); 1448 (δ C-H); 1098 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 3.50 (1H, ddd, J = 6.7, 9.3, 18.7 Hz, 1′′-H_A), 3.49 (1H, ddd, J = 6.7, 9.3, 18.7 Hz, 1′′-H_B), 3.16 (1H, dt, J = 3.7, 8.1 Hz, 1-H), 2.38 (1H, m, 2-H), 2.17 (2H, dt, J = 2.2, 6.9 Hz, 3′′-H_2), 1.98 - 1.88 (2H, m, 3-H_A, 6-H_A), 1.70 - 1.60 (2H, m, 4-H_A, 5-H_A), 1.59 (2H, dqd, J = 7.1, 7.1, 7.1 Hz, 2′′-H_2), 1.50 - 1.34 (5H, m, 3-H_B, 4′-H_2, 5′-H_2), 1.32 - 1.17 (3H, m, 4-H_B, 5-H_B, 6-H_B), 0.94 (3H, t, J = 7.4 Hz, 3′′-H_3), 0.90 ppm (3H, t, J = 7.2 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 82.4 (s, C-2′)*, 81.1 (s, C-1′)*, 80.1 (d, C-1), 71.1 (t, C-1′′), 35.1 (d, C-2), 31.2 (t), 30.8 (t), 30.2 (t), 24.0 (t), 23.3 (2t), 21.9 (t), 18.5 (t, C-3′) 13.6 (q, C-6′), 10.7 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 222 (24) [M^+], 193 (100), 179 (98), 165 (99), 163 (9), 141 (3).

(±)-*trans*-Ethoxy-2-(prop-1-ynyl)-cyclohexane (*trans*-8b)

Yield: 58%, colorless liquid. – R_f [*n*-pentane/diethyl ether (20:1)] = 0.31. – IR (film): $\tilde{\nu}$ = 2959, 2932, 2859 (ν C-H); 1446 (δ C-H); 1102 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 3.63 (1H, qd, J = 7.0, 9.4 Hz, 1′′-H_A), 3.60 (1H, qd, J = 7.0, 9.4 Hz, 1′′-H_B), 3.17 (1H, ddd, J = 4.1, 4.1, 12.5 Hz, 1-H), 2.34 (1H, m, 3-H), 1.96 (1H, m), 1.91 (1H, m), 1.81 (3H, d, J = 2.4 Hz, 3′-H_3), 1.68 (1H, m), 1.61 (1H, m), 1.37 (1H, ddt, J = 3.6, 10.0, 13.4 Hz), 1.31 - 1.23 (3H, m), 1.21 ppm (3H, t, J = 7.0 Hz, 2′′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 82.4 (s, C-1′)*, 79.9 (d, C-1), 76.3 (s, C-2′)*, 64.5 (t, C-1′′), 35.2 (d, C-2), 30.8 (t), 30.4 (t), 24.1 (t), 23.4 (t), 15.7 (q, C-2′′), 3.6 ppm (q, C-3′). – MS (70 eV); *m/z* (%) = 166 (13) [M^+], 151 (61), 137 (100), 121 (20).

(±)-*cis*-Propoxy-2-(hex-1-ynyl)-cyclohexane (*cis*-8a)

Yield: 88%, colorless liquid. – R_f [*n*-pentane/diethyl ether 40:1)] = 0.24. – IR (film): $\tilde{\nu}$ = 2958, 2933, 2858 (ν C-H); 1448 (δ C-H); 1110 cm^{-1} (ν C-O). – ^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 3.51 (1H, td, J = 6.8, 18.7 Hz, 1′′-H_A), 3.36 (1H, td, J = 6.8, 9.2 Hz, 1′′-H_B), 3.24 (1H, ddd, J = 3.8, 3.8, 9.3 Hz, 1-H), 2.91 (1H, m, 2-H), 2.19 (2H, dt, J = 2.3, 7.0 Hz, 3′-H_2), 1.84 - 1.67 (3H, m, 3-H_A, 4-H_A, 6-H_A), 1.56 (4H, m, 5-H_A, 6-H_B, 2′′-H_2), 1.52 - 1.34 (6H, m, 3-H_B, 4-H_B, 4′-H_2, 5′-H_2), 1.24 (1H, m, 5-H_B), 0.93 (3H, t, J = 7.4 Hz, 3′′-H_3), 0.90 ppm (3H, t, J = 7.3 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 82.5 (s, C-1′)*, 80.2 (s, C-2′)*, 78.2 (d, C-1), 69.9 (t, C-1′′), 32.6 (d, C-2), 31.3 (t), 29.9 (t), 28.6 (t), 23.2 (t), 22.1 (t), 22.0 (t), 21.9 (t), 18.6 (t, C-3′), 13.6 (q, C-6′), 10.6 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 222 (24) [M^+], 193 (84), 179 (90), 165 (94).

(±)-*cis*-Ethoxy-2-(prop-1-ynyl)-cyclohexane (*cis*-8b)

To a solution of 1.02 g (6.71 mmol) *cis*-ethoxy-2-ethynyl cyclohexane[15] in 25 mL abs. THF und 10 mL 1,3-dimethyl tetrahydro-2(1H)-pyrimidinone were added at -78°C 9 mL (14.4 mmol) *n*-butyl lithium (1.6N in *n*-hexane) and stirred for 45 min. 4.0 mL (64.26 mmol) methyl iodide were added and stirred for 30 min at -78°C. After warming up to rt water was added and the reaction mixure extracted with diethyl ether. The combined organic fractions were dried, concentrated, and the residue was purified by column chromatography [SiO_2, *n*-pentane/diethyl ether (30:1)] to yield 762 mg (4.59 mmol, 68%, R_f = 0.20) ***cis*-8b** as a colorless liquid.

IR (film): $\tilde{\nu}$ = 2934, 2857 (ν C-H); 1446 (δ C-H); 1371 (δ CH_3); 1110 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 3.62 (1H, qd, J = 7.0, 9.4 Hz, 1′′-H_A), 3.48 (1H, qd, J = 7.0, 9.4 Hz, 1′′-H_B), 3.24 (1H, td, J = 4.0, 9.1 Hz, 1-H), 2.95 (1H, m, 2-H), 1.83 (3H, d, J = 2.4 Hz, 3′-H_3), 1.88 (1H, m, 3-H_A), 1.79 - 1.56 (4H, m, 4-H_2, 5-H_A, 6-H_A), 1.47 - 1.33 (2H, m, 3-H_B, 5-H_B), 1.21 (1H, m, 6-H_B), 1.22 ppm (3H, t, J = 7.0 Hz, 2′′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 79.2 (s, C-1′)*, 78.2 (d, C-1), 77.9 (s, C-2′)*, 63.5 (t, C-1′′), 32.8 (d, C-2), 30.0 (t), 28.6 (t), 24.0 (t), 21.9 (t), 15.6 (q, C-2′′), 3.8 ppm (q, C-3′). – MS (CI); *m/z* (%) = 167 (7) [M^++H], 165 (32), 151 (18), 121 (50), 147 (38), 107 (100).

(±)-*trans*-Propoxy-2-(hex-1-ynyl)-cycloheptane (*trans*-9)

Yield: 90%, colorless liquid. – R_f [*n*-pentane/diethyl ether (30:1)] = 0.31. – IR (film): $\tilde{\nu}$ = 2958, 2930, 2860 (ν C-H); 1449 (δ C-H); 1090 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 3.44 (1H, ddd, J = 6.7, 6.7, 9.2 Hz, 1′′-H_A), 3.41 (1H, ddd, J = 6.1, 6.7, 6.7 Hz, 1-H), 3.40 (1H, ddd, J = 6.7, 6.7, 9.2 Hz, 1′′-H_B), 2.69 (1H, m, 2-H), 2.17 (2H, dt, J = 2.4, 6.9 Hz, 3′-H_2), 1.85 - 1.35 (16H, m), 0.93 (3H, t, J = 7.4 Hz, 3′′-H_3), 0.91 ppm (3H, t, J = 7.2 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 83.3 (s, C-1′)*, 83.1 (d, C-1), 81.4 (s, C-2′)*, 70.9 (t, C-1′′), 37.2 (d, C-2), 31.3 (t), 30.9 (t), 29.2 (t), 28.3 (t), 24.8 (t), 23.3 (t), 22.0 (t), 21.8 (t), 18.5 (t, C-3′), 13.7 (q, C-6′), 10.8 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 236 (9) [M^+], 207 (15), 193 (91), 179 (38), 177 (14).

(±)-*cis*-Propoxy-2-(hex-1-ynyl)-cycloheptane (*cis*-9)

Yield: 77%, colorless liquid. – R_f [*n*-pentane/diethyl ether (40:1)] = 0.26. – IR (Film): $\tilde{\nu}$ = 2958, 2930, 2860 (ν C-H); 1458 (δ C-H); 1093 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 3.46 (1H, ddd, J = 6.8, 6.8, 9.3 Hz, 1′′-H_A), 3.37 (1H, ddd, J = 6.8, 6.8, 9.3 Hz, 1′′-H_B), 3.32 (1H, ddd, J = 3.3, 3.7, 10.0 Hz, 1-H), 2.98 (1H, m, 2-H), 2.19 (2H, dt, J = 2.3, 7.1 Hz, 3′-H_2), 1.89 - 1.80 (2H, m, 3-H_A, 7-H_A), 1.76 (1H, m, 7-H_B), 1.59 (2H, tq, J = 6.7, 7.5 Hz, 2′′-H_2), 1.72 - 1.28 (11H, m), 0.92 (3H, t, J = 7.5 Hz, 3′′-H_3), 0.90 ppm (3H, t, J = 7.4 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 82.7 (s, C-1′)*, 82.0 (d, C-1), 80.6 (s, C-2′)*, 70.8 (t, C-1′′), 35.4 (d, C-2), 31.3 (t), 31.2 (t), 29.9 (t), 26.6 (t), 24.5 (t), 23.3 (t), 22.8 (t), 22.0 (t), 18.7 (t, C-3′), 13.7 (q, C-6′), 10.7 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 236 (23) [M^+], 207 (9), 193 (86), 179 (33), 177 (11).

General procedure for electrolysis experiments: The alkyne and lithium nitrate (2.5 eq.) were electrolyzed in a mixture of acetonitrile/water/diethyl ether (5:1:2, 15-20 mL/mmol alkyne). After thin layer chromatography indicated complete consumption of the alkyne (3-6 h) the reaction mixture was poured into brine and extracted several times with diethyl ether. The combined organic fractions were dried, evaporated and purified by column chromatography (SiO_2).

Reaction of $NO_3^\bullet$ with *cis*-7a:

(1R,3S*,4S*,5R*)-(±)-3-Methyl-4-(1-oxopentyl)-2-oxabicyclo[3.3.0]octane (12a):* Yield: 25%, colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.15. – IR (film): $\tilde{\nu}$ = 2958, 2930, 2872 (ν C-H); 1708 (ν C=O); 1465 (δ C-H); 1108 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 4.46 (1H, ddd, J = 1.2, 5.6, 6.8 Hz, 1-H), 3.91 (1H, qd, J = 6.0, 9.4 Hz, 3-H), 2.75 (1H, m, 5-H), 2.48 (1H, td, J = 7.4, 17.0 Hz, 2′-H_A), 2.45 (1H, td, J = 7.3, 17.0 Hz, 2′-H_B), 2.31 (1H, dd, J = 7.8, 9.4 Hz, 4-H), 1.85 (1H, m, 8-H_A), 1.71 - 1.60 (4H, m, 8-H_2, 7-H_2), 1.58 (2H, tdd, J = 7.4, 7.4, 15.0 Hz, 3′-H_2), 1.44 (1H, dddd, J = 5.4, 6.8, 6.8, 13.5 Hz, 8-H_B), 1.32 (2H, tq, J = 7.4, 7.4 Hz, 4′-H_2), 1.25 (3H, d, J = 5.8 Hz, 3-CH_3), 0.92 ppm (3H, t, J = 7.4 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 211.1 (s, C-1′), 84.5 (d, C-1), 77.7 (d, C-3), 66.9 (d, C-4), 48.9 (d, C-5), 43.4 (t), 33.6 (t), 33.0 (t), 25.5 (t), 23.6 (t), 22.3 (t), 19.0 (q, 3-CH_3), 13.9 ppm (q, C-5′). – MS (70 eV); *m/z* (%) = 210 (6) [M^+], 195 (18), 167 (1), 153 (36), 125 (6). – Anal. calcd. for $C_{13}H_{22}O_2$ (210.186): C 74.23, H 10.55; found: C 74.39, H 10.55.

Reaction of $NO_3^\bullet$ with *cis*-7b:

a) (1R,3S*,4S*,5R*)-(±)-3-Ethyl-4-(1-oxopentyl)-2-oxabicyclo[3.3.0]octane (12b):* Yield: 35%, colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.20. – IR (film): $\tilde{\nu}$ = 2958, 2930, 2873 (ν C-H); 1708 (ν C=O); 1463 (δ CH_2, CH_3); 1117, 1052 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 4.40 (1H, ddd, J = 1.1, 5.6, 6.6 Hz, 1-H), 3.75 (1H, ddd, J = 5.8, 5.8, 9.4 Hz, 3-H), 2.62 (1H, m, 5-H), 2.42 - 2.34 (2H, m, 2′-H_2), 2.33 (1H, dd, J = 7.5, 9.4 Hz, 4-H), 1.80 (1H, m, 8-H_A), 1.60 - 1.45 (8H, m), 1.31 - 1.18 (2H, m, 4′-H_2), 1.39 (1H, m, 3′-H_B), 0.86 (3H, t, J = 7.5 Hz, 2′′-H_3), 0.85 ppm (3H, t, J = 7.3 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 211.4 (s, C-1′), 84.5 (d, C-1), 83.1 (d, C-3), 64.8 (d, C-4), 49.0 (d, C-5), 43.5 (t, C-7), 33.6 (t), 33.1 (t), 26.8 (t), 25.5 (t), 23.7 (t), 22.3 (t), 13.9 (q, C-2′′), 10.4 ppm (q, C-5′). – MS (70 eV); *m/z* (%) = 224 (6) [M^+], 195 (50), 157 (100), 125 (2). – Anal. calcd. for $C_{14}H_{24}O_2$ (224.202): C 74.94, H 10.78; found: 74.81, H 10.76.

b) (±)-cis-Propoxy-2-(1,2-dioxohexyl)-cyclopentane (cis-21a): Yield: 5%, yellow liquid. – R_f [*n*-pentane/diethyl ether (3:1)] = 0.50. – IR (film): $\tilde{\nu}$ = 2960, 2932, 2874 (ν C-H); 1714 (ν C=O); 1466 (δ C-H), 1081 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 4.30 (1H, ddd, J = 2.8, 4.6, 7.3 Hz, 1-H), 3.71 (1H, td, J = 7.3, 8.9 Hz, 2-H), 3.28 (1H, td, J = 6.9, 9.1 Hz, 1′′-H_A), 3.08 (1H, td, J = 6.5, 9.1 Hz, 1′′-H_B), 2.91 (1H, ddd, J = 6.2, 8.9, 18.3 Hz, 3′-H_A), 2.54 (1H, ddd, J = 5.9, 8.9, 18.3 Hz, 3′-H_B), 2.21 (1H, m, 3-H_A), 1.78 - 1.64 (3H, m, 3-H_B, 5-H), 1.64 - 1.50 (4H, m, 4-H_2, 4′-H_2), 1.40 (2H, qt, J = 7.4, 7.4 Hz, 5′-H_2), 1.35 (2H, qt, J = 7.4, 7.4 Hz, 2′′-H_2), 0.92 (3H, t, J = 7.4 Hz, 3′′-H_3), 0.83 ppm (3H, t, J = 7.4 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 200.8 (s, C-1′)*, 199.4 (s, C-2′)*, 82. 2 (d, C-1), 70.7 (t, C-2′′), 50.0 (d, C-2), 35.6 (t, C-3′), 31.9 (t), 24.9 (t), 23.6 (t), 22.9 (t), 22.8 (t), 22.3 (t), 13.8 (q, C-6′), 10.5 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 240 (5) [M^+], 155 (33), 113 (100), 85 (50).

Reaction of $NO_3^\bullet$ with *cis*-7c:

(1R,3R*,4S*,5R*)-(±)-3-Methoxy-4-(1-oxopentyl)-2-oxabicyclo[3.3.0]octane (13a)* and *(1R*,3R*, 4R*, 5R*)-(±)-3-methoxy-4-(1-oxopentyl)-2-oxabicyclo[3.3.0]octane (13b):* Yield: 28% (**13a** : **13b** = 2.4:1), colorless oil. – R_f [*n*-pentane/diethyl ether (3:1)] = 0.38. – **13a**: ^1H NMR ($CDCl_3$, 300 MHz): δ = 4.95 (1H, d, J = 3.0 Hz, 3-

H), 4.64 (1H, m, 1-H), 3.29 (3H, s, OCH_3), 2.92 (1H, dd, J = 3.0, 4.1 Hz, 4-H), 2.79 (1H, tdd, J = 4.0, 7.1, 8.3 Hz, 5-H), 2.50 (2H, m, 2′-H_2), 0.91 ppm (3H, t, J = 7.3 Hz, 5′-H_3). – ^{13}C-NMR ($CDCl_3$, 75.5 MHz): δ = 209.0 (s, C-1′), 107.2 (d, C-1), 86.0 (d, C-3), 65.4 (d, C-4), 55.7 (q, OCH_3), 44.5 (d, C-5), 42.1 (t, C-2), 34.4 (t), 32.8 (t), 26.5 (t), 23.9 (t), 22.3 (t), 13.8 ppm (q, C-5′). – **13b**: ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 5.25 (1H, d, J = 5.1 Hz, 3-H), 4.66 (1H, m, 1-H), 3.38 (3H, s, OCH_3), 3.30 (1H, m, 5-H), 2.78 (1H, dd, J = 5.1, 7.5 Hz, 4-H), 2.51 - 2.33 (2H, m, 2′-H_2), 0.91 ppm (3H, t, J = 7.3 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 205.1 (s, C-1′), 104.6 (d, C-1), 84.5 (d, C-3), 64.9 (d, C-4), 54.4 (q, OCH_3), 42.2 (d, C-5), 40.5 (t, C-2), 33.5 (t), 32.7 (t), 25.6 (t), 23.3 (t), 22.2 (t), 13.8 ppm (q, C-5′). – Diastereomeric mixture: IR (film): $\tilde{\nu}$ = 2956, 2871 (ν C-H); 1715 (ν C=O); 1466 (δ C-H); 1097, 1037 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 1.91 - 1.46 (8H, m, 3′-H_2, 6-H_2, 7-H_2, 8-H_2), 1.40 - 1.20 ppm (2H, m, 4′-H_2). – MS (70 eV); *m/z* (%) = 226 (5) [M^+], 225 (15), 195 (10). – $C_{12}H_{19}O_2$ [M^+-OCH_3]: calcd. 195.13850; found 195.13850 (MS).

Reaction of $NO_3^•$ with *cis*-7d:

(1R,3S*,4R*,5R*)-(±)-3-Cyanyl-4-(1-oxopentyl)-2-oxabicyclo[3.3.0]octane (**14a**):* Yield: 21%, colorless oil. – R_f [dichloromethane/diethyl ether/*n*-pentane (10:0.1:6)] = 0.33. – IR (film): $\tilde{\nu}$ = 2958, 2930, 2872 (ν C-H); 1711 (ν C=O); 1466 (δ C-H); 1108, 1074 cm^{-1} (ν C-O). – ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 4.70 (1H, d, J = 7.4 Hz, 3-H), 4.55 (1H, ddd, J = 1.2, 5.5, 6.7 Hz, 1-H), 3.15 (1H, dd, J = 5.8, 7.4 Hz, 4-H), 2.74 (1H, m, 5-H), 2.57 (1H, td, J = 7.4, 17.3 Hz, 2′-H_A), 2.53 (1H, td, J = 7.1, 17.3 Hz, 2′-H_B), 1.96 (1H, m, 8-H_A), 1.89 - 1.67 (4H, m, 6-H_2, 7-H_2), 1.66 - 1.55 (3H, m), 1.35 (2H, qt, J = 7.4, 7.4 Hz, 4′-H_2), 0.93 ppm (3H, t, J = 7.3 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 206.9 (s, C-1′), 117.9 (s, CN), 87.3 (d, C-3), 67.2 (d, C-1), 63.5 (d, C-4), 47.7 (d, C-5), 42.4 (t, C-2′), 33.3 (t), 32.8 (t), 25.4 (t), 23.7 (t), 22.2 (t), 13.8 ppm (q, C-5′). – MS (70 eV); *m/z* (%) = 221 (33) [M^+], 164 (78), 136 (80), 85 (100). – Anal. calcd. for $C_{13}H_{19}NO_2$ (221.172): C 70.54, H 8.66; found: C 70.56, H 8.60.

Reaction of $NO_3^•$ with 20a:

(1R,3S*,4S*,5R*)-(±)-3-[D_3]Methyl-4-(1-oxopentyl)-2-oxa[4-D_1]bicyclo[3.3.0]octane (**12c**):* Yield: 29%, colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.20. – ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 4.46 (1H, ddd, J = 0.9, 5.5, 7.0 Hz, 1-H), 2.75 (1H, m, 5-H), 2.47 (1H, td, J = 7.4, 17.0 Hz, 2′-H_A), 2.45 (1H, td, J = 7.3, 17.0 Hz, 2′-H_B), 1.86 (1H, m, 8-H_A), 1.73 - 1.55 (6H, m, 3′-H_2, 7-H_2, 6-H_2), 1.44 (1H, dddd, J = 5.6, 6.6, 6.6, 13.2 Hz, 8-H_B), 1.32 (2H, tq, J = 7.4, 7.41 Hz, 4′-H_2), 0.92 ppm (3H, t, J = 7.3 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 211.1 (s, C-1′), 84.6 (d, C-1), 66.6 (s, C-3)*, 66.3 (s, C-4)*, 66.1 (s, C-1′′)*, 48.8 (d, C-5), 43.4 (t, C-2′), 33.6 (t), 32.9 (t), 25.5 (t), 23.6 (t), 22.3 (t), 13.9 ppm (q, C-5′). – MS (CI); *m/z* (%) = 216 (100) [M^++H].

Reaction of $NO_3^•$ with 20b:

(1R,3S*,4S*,5R*)-(±)-3-Ethyl-4-(1-oxopentyl)-2-oxa[3-D_1]bicyclo[3.3.0]octane (**12d**)* and *(1R*,3S*,4S*,5R*)-(±)-3-ethyl-4-(1-oxopentyl)-2-oxa[4-D_1]bicyclo[3.3.0]octane (**12e**):* Yield: 34% (**12d** : **12e** = 3:1), colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.20. – ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 4.46 (1H, dddd, J = 1.2, 1.2, 5.5, 6.7 Hz, 1-H), 3.82 ($^1/_4$H, m, 3-H), 2.69 (1H, m, 5-H), 2.47 (2H, dt, J = 1.6, 7.2 Hz, 2′-H_2), 2.40 ($^3/_4$H, m, 4-H), 1.86 (1H, m, 8-H_A), 1.71 - 1.41 (9H, m), 1.32 (2H, qt, J = 7.4, 7.4 Hz, 4′-H_2), 0.93 (3H, t, J = 7.5 Hz, 2′′-H_3), 0.92 ppm (3H, t, J = 7.4 Hz, 5′-H_3). – MS (CI); *m/z* (%) = 226 (100) [M^++H].

Reaction of $NO_3^•$ with *trans*-8a:

a) (1R,6S*,8R*,9R*)-(±)-8-Ethyl-9-(1-oxopentyl)-7-oxabicyclo[4.3.0]nonane (16a):* Yield: 34%, colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)]. = 0.48. – IR (film): $\tilde{\nu}$ = 2933, 2859 (ν C-H); 1709 (ν C=O); 1452 (δ C-H); 1126, 1065 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 4.13 (1H, ddd, J = 3.8, 9.5, 9.5 Hz, 8-H), 3.13 (1H, ddd, J = 3.8, 9.9, 10.8 Hz, 6-H), 3.00 (1H, dd, J = 9.5, 11.1 Hz, 9-H), 2.40 (2H, t, J = 7.6 Hz, 2′-H_2), 2.11 (1H, m, 5-H_A), 1.87 - 1.75 (3H, m, 1-H, 2-H_A, 4-H_A), 1.72 - 1.66 (2H, m, 3-H_A, 5-H_B), 1.64 - 1.48 (2H, m, 3′-H_2), 1.46 - 1.13 (6H, m, 1′′-H_2, 4′-H_2, 4-H_B, 2-H_B), 1.04 (1H, m, 3-H_B), 0.92 (3H, t, J = 7.3 Hz, 2′′-H_3), 0.91 ppm (3H, t, J = 7.2 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 210.0 (s, C-1′), 82.4 (d, C-6), 80.0 (d, C-8), 58.9 (d, C-9), 47.3 (d, C-1), 45.2 (t, C-2′), 31.4 (t), 28.2 (t), 26.2 (t), 25.6 (t), 25.5 (t), 24.1 (t), 22.3 (t), 13.9 (q, C-5′), 10.8 ppm (q, C-2′′). – MS (70 eV); *m/z* (%) = 238 (4) [M^+], 181 (60), 125 (4), 85 (100). – Anal. calcd. for $C_{15}H_{26}O_2$ (238.219): C 75.57, H 11.00; found: C 75.64, H 10.94.

b) (±)-cis-Propoxy-2-(1,2-dioxohexyl)-cyclohexane (trans-21b): Yield: ca. 10%, yellow oil. – IR (film): $\tilde{\nu}$ = 2960, 2934, 2861 (ν C-H); 1711 (ν C=O); 1451 (δ C-H); 1097 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 3.48 (1H, td, J = 6.7, 9.1 Hz, 1′′-H_A), 3.40 (1H, m, 1-H), 3.27 (1H, ddd, J = 3.5, 10.2, 11.6 Hz, 2-H), 3.15 (1H, td, J = 6.7, 9.1 Hz, 1′′-H_B), 2.77 (1H, td, J = 7.4, 17.6 Hz, 3′-H_A), 2.64 (1H, td, J = 7.3, 17.6 Hz, 3′-H_B), 2.17 (1H, m, 3-H_A), 1.84 - 1.17 (13H, m, 3-H_B, 4-H_2, 5-H_2, 6-H_2, 2'-H_2, 4′-H_2, 5′-H_2), 0.91 (3H, t, J = 7.3 Hz, 3′-H_3), 0.82 ppm (3H, t, J = 7.4 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 203.6 (s, C-1′)*, 200.4 (s, C-2′)*, 79.7 (d, C-1), 70.1 (t, C-1′′), 49.2 (d, C-2), 35.8 (t, C-3′), 30.9 (t), 28.0 (t), 24.9 (t), 24.6 (t), 24.2 (t), 23.2 (t), 22.3 (t), 13.8 (q, C-6′), 10.5 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 254 (14) [M^+], 140 (21), 85 (17).

Reaction of $NO_3^•$ with *trans*-8b:

(1R,6S*,8R*,9R*)-(±)-8-Methyl-9-(1-oxoethyl)-7-oxabicyclo[4.3.0]nonane (16b):* Yield: 27%, colorless oil. – R_f [*n*-pentane/diethyl ether (3:1)] = 0.11. – IR (film): $\tilde{\nu}$ = 2933, 2859 (ν C-H), 1711 (ν C=O); 1446, 1356 (δ C-H); 1166, 1120, 1069 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.39 (1H, dq, J = 6.4, 9.6 Hz, 8-H), 3.08 (1H, ddd, J = 3.8, 10.0, 11.0 Hz, 6-H), 2.94 (1H, dd, J = 9.6, 11.2 Hz, 9-H), 2.11 (3H, s, 2′′-H_3), 2.02 (1H, dddd, J = 1.2, 3.8, 7.2, 8.7 Hz, 1-H), 1.80 - 1.72 (3H, m), 1.63 (1H, m), 1.34 - 1.11 (4H, m), 1.00 ppm (3H, t, J = 6.4 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 207.3 (s, C-1′), 82.4 (d, C-6), 73.6 (d, C-8), 59.7 (d, C-9), 46.0 (t, C-2′), 31.8 (q, C-3′), 31.2 (t), 27.9 (t), 25.3 (t), 23.9 (t), 18.4 ppm (q, C-2′′). – MS (CI); *m/z* (%) = 183 (46) [M^++H], 181 (41), 155 (12), 139 (100).

Reaction of $NO_3^•$ with *cis*-8a:

(1R,6R*,8S*,9R*)-(±)-8-Ethyl-9-(1-oxopentyl)-7-oxabicyclo[4.3.0]nonane (15):* Yield: 11%, colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.26. – IR (film): $\tilde{\nu}$ = 2932, 2861 (ν C-H), 1709 (ν C=O); 1463 (δ C-H); 1069 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.00 (1H, ddd, J = 6.4, 6.4, 6.4 Hz, 8-H), 3.88 (1H, ddd, J = 4.7, 4.7, 4.7 Hz, 6-H), 2.54 (1H, dd, J = 3.0, 6.4 Hz, 9-H), 2.47 (1H, t, J = 6.7 Hz, 2′-H_A), 2.42 (1H, ddd, J = 7.3, 7.3, 17.0 Hz, 2′-H_B), 2.11 (1H, dddd, J = 3.0, 4.7, 5.9, 10.6 Hz, 1-H), 1.92 (1H, ddddd, J = 1.4, 3.8, 3.8 , 3.8, 14.3 Hz, 5-H_A), 1.75 (1H, qdd, J = 6.4, 7.3, 14.4 Hz, 1′′-H_A), 1.68 - 1.45 (7H, m, 1′′-H_B, 3′-H_2, 5-H_A, 3-H_2, 5-H_B), 1.49 - 1.16 (3H, m, 5-H_b, 4-H_2), 1.31 (2H, qt, J = 7.3, 7.3 Hz, 4′-H_2), 0.95 (3H, t, J = 7.5 Hz, 2′′-H_3), 0.91 ppm (3H, t, J = 7.3 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 211.0 (s, C-1′), 81.3 (d, C-6), 76.4 (d, C-8), 62.9 (d, C-9), 42.8 (t. C-2′), 42.7 (d, C-1), 29.3 (t), 29.2 (t), 28.1 (t), 25.7 (t), 24.4 (t), 22.3 (t), 20.7 (t), 13.9 (q, C-5′), 10.5 ppm (q, C-2′′). – MS (CI); *m/z* (%) = 239 (100) [M^++H]. – Anal. calcd. for $C_{15}H_{26}O_2$ (238.219): C 75.57, H 11.00; found: C 75.54, H 11.00.

Reaction of $NO_3^•$ with *cis*-8b:

(1R,6R*,8R*,9R*)-(±)-8-Methyl-9-(1-oxoethyl)-7-oxabicyclo[4.3.0]nonane (14b):* Yield: 9%, colorless oil. - R_f [*n*-pentane/diethyl ether (6:1)] = 0.29. – IR (film): $\tilde{\nu}$ = 2931, 2856 (ν C-H); 1710 (ν C=O); 1447, 1356 (δ C-H); 1158, 1089, 991, 607 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.06 (1H, dq, J = 6.3, 6.4 Hz, 8-H), 3.78 (1H, ddd, J = 4.3, 4.3, 4.6 Hz, 6-H), 2.41 (1H, dd, J = 3.1, 6.4 Hz, 9-H), 2.16 (1H, dddd, J = 3.1, 4.6, 6.1, 10.8 Hz, 1-H), 2.11 (3H, s, 2′-H_3), 1.84 (1H, ddddd, J = 1.4, 3.5, 3.8 ,3.8, 15.4 Hz, 5-H_A), 1.63 - 1.26 (9H, m), 1.17 ppm (1H, m). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 207.2 (s, C-1′), 75.8 (d, C-6), 74.8 (d, C-8), 64.9 (d, C-9), 41.3 (t, C-2′), 28.7 (q, C-2′′), 28.3 (t), 27.0 (t), 23.3 (t), 21.2 (q, C-2′′), 19.6 ppm (t). – MS (CI); *m/z* (%) = 183 (100) [M^++H].

Reaction of $NO_3^•$ with *trans*-9:

a) (1R,7S*,9R*,10R*)-(±)-9-Ethyl-10-(1-oxopentyl)-8-oxabicyclo[5.3.0]decane (16c):* Yield: 16%, colorless oil. – R_f [dichloromethane/diethyl ether/*n*-pentane (50:1:25)] = 0.42. – IR (film): $\tilde{\nu}$ = 2930, 2859 (ν C-H); 1711 (ν C=O); 1454 (δ C-H); 1126, 1037 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.05 (1H, ddd, J = 3.9, 8.5, 9.6 Hz, 9-H), 3.61 (1H, ddd, J = 4.5, 9.6, 9.6 Hz, 7-H), 3.03 (1H, dd, J = 8.5, 9.6 Hz, 10-H), 2.41 (1H, ddd, J = 6.8, 8.4, 16.8 Hz, 2′-H_A), 2.38 (1H, ddd, J = 6.5, 8.3, 16.8 Hz, 2′-H_B), 2.34 (1H, dddd; J = 4.3, 9.6, 9.6, 11.3 Hz, 1-H), 2.19 (1H, m, 2-H_A), 1.79 (1H, ddd, J = 4.3, 6.4,13.6 Hz, 6-H_A), 1.68 (1H, m, 3-H_A), 1.60 - 1.45 (8H, m, 3′-H_2, 4′-H_A, 5-H_2, 4-H_A, 3-H_B, 2-H_B), 1.38 (1H, qdd J = 4.4, 9.6, 13.6 Hz, 1′′-H_A), 1.34 - 1.28 (2H, m, 4′-H_B, 4-H_B), 1.22 (1H, dqd, J = 3.9, 7.4, 13.6 Hz, 1′′-H_B), 1.17 (1H, m, 6-H_B), 0.92 (3H, t, J = 7.4 Hz, 2′′-H_3), 0.91 ppm (3H, t, J = 7.4 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 209.9 (s, C-1′), 84.2 (d, C-7), 80.6 (d, C-9), 62.8 (d, C-10), 46.5 (d, C-1), 44.6 (t, C-2′), 33.9 (t), 29.4 (t), 27.6 (t), 26.1 (t), 25.7 (t), 25.6 (t), 25.2 (t), 22.4 (t), 14.0 (q, C-5′), 10.8 ppm (q, C-2′′). – MS (70 eV); *m/z* (%) = 252 (8) [M^+], 223 (32), 209 (1), 195 (21), 167 (4), 85 (100). – $C_{16}H_{28}O_2$: calcd. 252.20892; found 252.20880 (MS).

b) (±)-trans-Propoxy-2-(1,2-dioxohexyl)-cycloheptane (trans-21c): Yield: 5%, yellow oil. – R_f [*n*-pentane/diethyl ether (3:1)] = 0.68. – IR (film): $\tilde{\nu}$ = 2960, 2932, 2863 (ν C-H); 1712 (ν C=O); 1458 (δ C-H); 1087 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 300 MHz): δ = 3.62 (1H, ddd, J = 2.5, 8.1, 9.6 Hz, 1-H), 3.40 (1H, m, 2-H), 3.39 (1H, ddd, J = 6.8, 6.8, 9.1 Hz, 1′′H_A), 3.10 (1H, ddd, J = 6.7, 6.7, 9.1 Hz, 1′′-H_B), 2.76 (1H, ddd, J = 7.5, 7.5, 17.9 Hz, 3′-H_A), 2.67 (1H, ddd, J = 7.4, 7.4, 17.9 Hz, 3′-H_B), 1.97 (1H, m, 3-H_A), 1.70 - 1.52 (11H, m, 3-H_B, 4-H_2, 5-H_2, 6-H_2, 7-H_2, 4′-H_2), 1.48 - 1.28 (4H, m, 2′′-H_2, 5′-H_2), 0.92 (3H, t, J = 7.3 Hz, 3′′-H_3), 0.81 ppm (3H, t, J = 7.4 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 202.7 (s, C-1′)*, 200.3 (s, C-2′)*, 81.9 (d, C-1), 70.5 (t, C-1′′), 51.0 (d, C-2), 35.9 (t, C-3′), 31.9 (t), 27.9 (t), 26.6 (t), 26.3 (t), 25.0 (t), 23.1 (t), 22.8 (t), 22.3 (t), 13.8 (q, C-6′), 10.6 ppm (q, C-2′′). – MS (70 eV); *m/z* (%) = 268 (5) [M^+], 183 (21), 113 (3), 85 (13).

c) (±)-trans-2-(2-Oxohexyl)-cycloheptyl propionate (22): Yield: 2%. – R_f [*n*-pentane/diethyl ether (7:1)] = 0.18. – IR (film): $\tilde{\nu}$ = 2931, 2860 (ν C-H); 1732, 1714 (ν C=O); 1461 (δ C-H); 1183, 1080 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.65 (1H, ddd, J = 3.9, 7.0, 9.0 Hz, 1-H), 2.42 (1H, dd, J = 3.8, 16.2 Hz, 1′-H_A), 2.37 (2H, ddd, J = 2.2, 7.5, 7.5 Hz, 3′-H_2), 2.32 (1H, dd, J = 9.0, 16.2 Hz, 1′-H_B), 2.28 (2H, q, J = 7.6 Hz, 2′′-H_2), 2.26 (1H, dddd, J = 3.1, 4.0, 9.0, 17.9 Hz, 2-H), 1.78 (1H, dddd, J = 2.7, 3.9, 8.1, 14.5 Hz, 7-H_A), 1.73 (1H, dddd, J = 2.5, 7.0, 9.6, 14.5 Hz, 7-H_B), 1.71 - 1.60 (3H, m), 1.55 (2H, dddd, J = 1.7, 7.5, 7.5, 14.7 Hz, 4′-H_2), 1.58 - 1.38 (4H, m), 1.30 (2H, tq, J = 7.4, 7.4 Hz, 5′-H_2), 1.27 (1H, m, 3-H_B), 1.12 (3H, t, J = 7.6 Hz, 3′′-H_3), 0.90 ppm (3H, t, J = 7.4 Hz, 6′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 210.4 (s, C-2′), 174.1 (s, C-1′′), 78.4 (d, C-1), 47.5 (t, C-1′), 43.0 (t, C-3′), 39.8 (d, C-2), 33.0 (t, C-7), 30.1 (t, C-3), 28.5 (t, C-5), 28.0 (t, C-2′′), 26.4 (t, C-4), 25.9 (t, C-4′), 22.5 (t, C-6), 22.4 (t, C-5′), 13.9 (q, C-6′), 9.2 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 268 (1) [M^+], 239 (1), 211 (11), 195 (8), 85 (100).

Reaction of $NO_3^\bullet$ with *cis*-9:

(1R,7R*,9R*,10R*)-(±)-9-Ethyl-10-(1-oxopentyl)-8-oxabicyclo[5.3.0]decane (14c):* Yield: 17%, colorless oil. – R_f [*n*-pentane/diethyl ether (10:1)] = 0.29. – IR (film): $\tilde{\nu}$ = 2958, 2926, 2853 (ν C-H); 1708 (ν C=O); 1462 (δ C-H); 1052 cm^{-1} (ν C-O). – ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.10 (1H, ddd, J = 4.3, 8.0, 10.7 Hz, 7-H), 3.84 (1H, ddd, J = 5.1, 6.7, 8.4 Hz, 9-H), 2.51 (1H, dddd, J = 3.7, 8.4, 8.4, 10.7 Hz, 1-H), 2.48 (1H, dd, J = 8.4, 8.4 Hz, 10-H), 2.47 (1H, ddd, J = 7.4, 7.4, 17.2 Hz, 2′-H_A), 2.43 (1H, ddd, J = 7.3, 7.3, 17.2 Hz, 2′-H_B), 1.94 (1H, dddd, J = 1.3, 4.3, 8.3, 13.8 Hz, 6-H_A), 1.79 (1H, ddddd, J = 1.4, 2.9, 5.7, 5.7, 7.7 Hz, 5-H_A), 1.78 - 1.71 (2H, m, 4-H_A, 3-H_A), 1.65 - 1.49 (7H, m, 1′′-H_2, 3′-H_2, 2-H_2, 6-H_B), 1.31 (2H, td, J = 7.5, 7.5 Hz. 4′-H_2), 1.29 (1H, m, 4-H_B), 1.24 - 1.13 (2H, m, 5-H_B, 3-H_B), 0.93 (3H, t, J = 7.5 Hz, 2′′-H_3), 0.91 ppm (t, J = 7.5 Hz, 5′-H_3). – ^{13}C NMR ($CDCl_3$, 125.8 MHz): δ = 211.4 (s, C-1′), 82.4 (d, C-9)*, 82.3 (d, C-7)*, 64.9 (d, C-10), 49.6 (d, C-1), 44.0 (t, C-2′′), 31.9 (t), 31.2 (t), 31.0 (t), 28.6 (t), 27.4 (t), 25.4 (t), 24.5 (t), 22.3 (t), 13.9 (q, C-5′), 10.3 ppm (q, C-3′′). – MS (70 eV); *m/z* (%) = 252 (4) [M^+], 223 (10), 195 (7), 167 (5), 85 (33). – Anal. calcd. for $C_{16}H_{28}O_2$ (252.236): C 76.13, H 11.19; found: C 76.18, H 11.19.

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References and Notes

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