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REVIEW ARTICLE

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Memory of chirality in reactions involving monoradicals

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ABSTRACT

The effects of memory of chirality (MoC) in reactions involving monoradical species are reviewed here. Reactions involving a nonracemic chiral starting material bearing a single stereogenic element such as a chiral center or chiral axis directly involved in the new bond formation are discussed. These reactions lead to a nonracemic product via an intermediate susceptible to rapid racemization. Memory of chirality has been observed in cyclic radicals, aryl, ester/amide substituted acyclic radicals, and benzylic radicals at temperatures up to 130 °C.

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Introduction

Stereoselective synthesis has been during the last 50 years one of the most important and challenging research field in organic synthesis. A special care has been dedicated to the transformation of enantiomerically pure chiral molecules without racemization. When a single chiral element (such as a chiral center) is present in the molecule, reactions involving this element have to be stereospecific to avoid any degradation of enantiomeric purity. This is usually achieved by using concerted reactions where bond cleavage and bond formation are taking place at the same time via a unique reaction pathway as for instance the backside nucleophilic attack at a carbon center bearing a leaving group in the S_N2 reaction. Reaction pathways involving the formation of a planar unit at the original asymmetric center (enolate anions, cations, radicals) have to be avoided. However, unexpected retention of the optical activity of products resulting from such intermediates has been observed and this has led to the concept of memory of chirality (MoC). This concept was proposed by Fuji and coworkers during their work on alkylation of enolates and it represents a challenging facet of stereoselective synthesis with interesting mechanistic and synthetic implications [1]. The phenomenon was already reported by Seebach and Wasmuth in the alkylation of di-*tert*-butyl *N*-formylaspartate involving a sp^2-hybridized enolate intermediate [2] and by Leuchs [3] and Marquet as well as coworkers [4,5] in the halogenation of chiral 2-benzylated-indan-1-ones involving an enol intermediate. Other examples in the field of diradical chemistry were discovered early by Jones in the thermal and by Rinehard and van Auken in the light induced decomposition of pyrazolines leading to cyclopropane [6,7], as well as by Jeger and coworkers during the photochemical formation of cyclobutanols from saturated ketones [8]. Nowadays, examples of MoC involving enolates [9], carbenium ions [10], radicals [11], radical cations [12], and diradicals [6] are known. The general field of MoC has been reviewed in 2005 by Carlier and coworkers [13] and very recently during the writing of this manuscript by Alezra and Kawabata [14]. In this review, we will focus on reactions involving monoradicals species. The chemistry of diradical intermediates as well as radical cations will be discussed in a forthcoming review article. The reactions presented here adhere to the following definition of MoC processes: reactions involving a nonracemic chiral starting material bearing a single chiral element directly involved in the new bond formation leading to a nonracemic product via an intermediate susceptible to racemize by way of a change of conformation[1].

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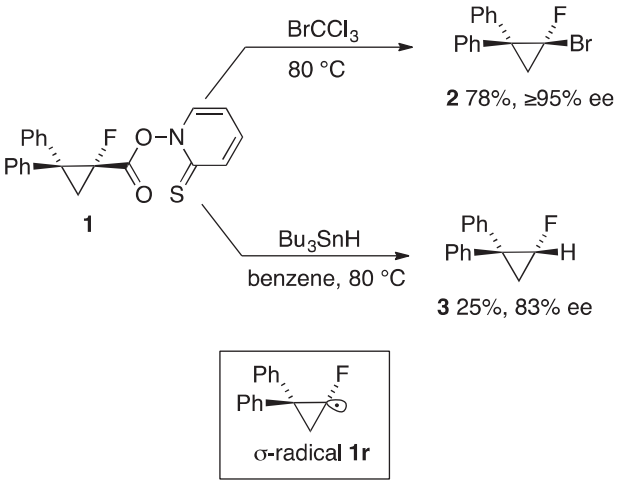
[1]Single diastereomers may also show memory of chirality if only one chiral element is involved in a diastereospecific new bond formation via an intermediate susceptible to epimerize via a change of conformation (see Scheme 2 for such an example).

This definition is more general than the one of Fuji [9] and Carlier [13] who considered only trigonalization of asymmetric centers (our definition also encompasses chiral axes and planes) and differs strongly from the one of Shi and coworkers [15] who consider also concerted reactions that do not involve an intermediate susceptible to rapid racemization by way of a conformational change (i.e. stereospecific reactions). We believe that our simple and clearly restrictive definition of the term *memory of chirality* keeps the original meaning of Fuji [9] and Carlier's [13] definitions without going into the drifting off point as described by Cozzi and Siegel who advise chemists to stop using this term [16]. The concept of MoC is particularly useful in the field of radical reactions that were until the beginning of the 1980s considered to take place in a stereorandom manner [17]. Indeed, even though the structure of most alkyl radicals is pyramidal [18], their umbrella inversion barrier is very low as demonstrated experimentally for the tert-butyl radical by Griller et al. (inversion barrier of 0.51 kcal/mol) [19] as well as by calculations (inversion barriers of 1.1 kcal/mol) [20]. As a consequence, racemization is often suggested as evidence for the involvement of radical intermediates in a reaction and has been used as a synthetic tool for efficient racemization processes [21]. The design of MoC in radical reactions is at first sight particularly challenging since radicals are configurationally unstable.

Cycloalkyl radicals

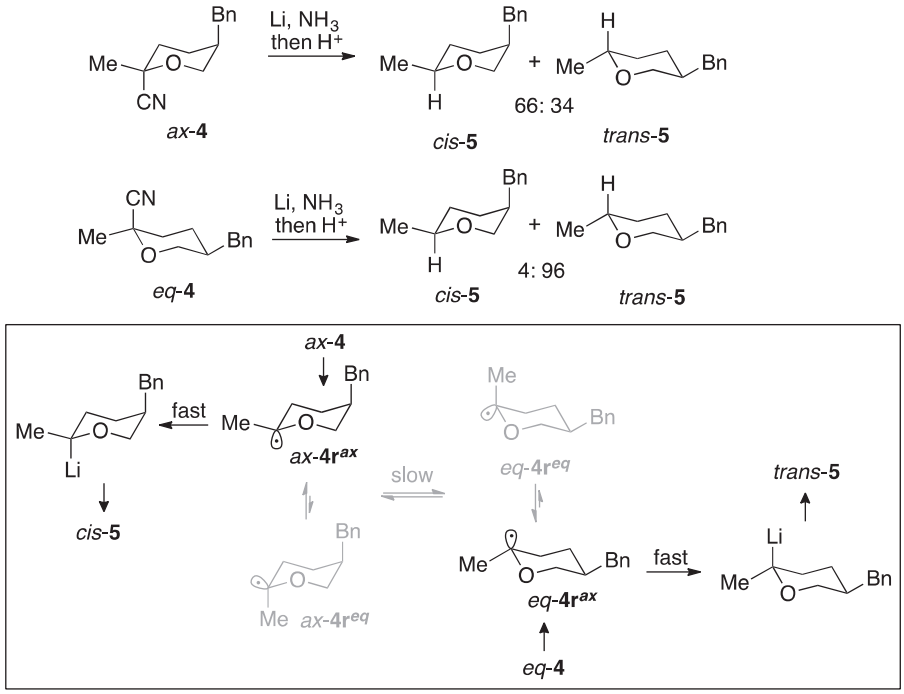
Due to the very high rate constants of radical processes, reactions involving cycloalkyl radicals may in a few cases compete with epimerization processes. Cyclopropyl radicals represent the earliest class of cycloalkyl radicals showing MoC effects and this topic has been reviewed by Walborsky [22]. They were first examined by Ando et al. in 1970 who showed that the dehalogenation of 1-halo-1-fluorocyclopropane was occurring with retention of configuration and that the level of retention of configuration was influenced by the source of hydrogen atom [23]. For instance, Bu_3SnH afforded the fluorocyclopropane with full retention of configuration at 130–140 °C. By using a slower hydrogen donor such as tributylsilane, partial epimerization of the intermediate radical could be detected. Walborsky reported that the decarboxylation of the Barton ester of 1-fluoro-2,2-diphenylcyclopropane **1** in $BrCCl_3$ afforded the bromide **2** as a single enantiomer (Scheme 1) [24]. The decarboxylation of **1** in refluxing benzene using Bu_3SnH to trap the radical afforded the fluorocyclopropane **3** in 83% ee, demonstrating again that the reactivity of the trap was influencing the level



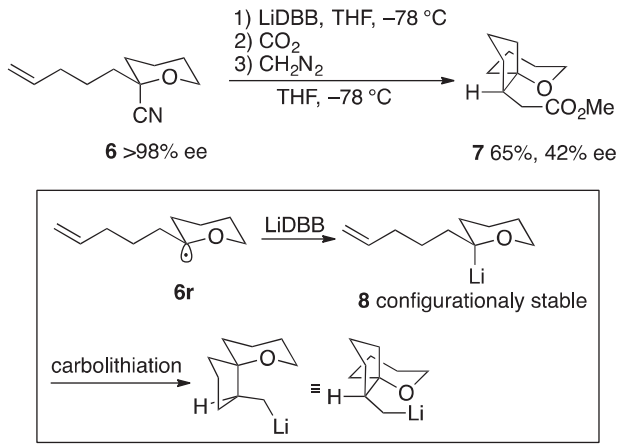
Scheme 1. MoC in reaction involving fluorinated cyclopropyl radicals.

of MoC. The presence of a fluorine atom, which decreases the inversion frequency of the cyclopropyl σ-radical **1r** favors strongly MoC [25]. Related MoC effects have been observed with a methoxy-substituted cyclopropyl radical, although to a much lower extent than the fluorinated analogue [22]. Interestingly, MoC has been observed in the metal-mediated reductive lithiation involving the fast epimerizing 1-methylcyclopropyl radical [26,27]. Reactions involving dissolved metals showing MoC have also been reported [28], but the interpretation of the results is more complex [29].

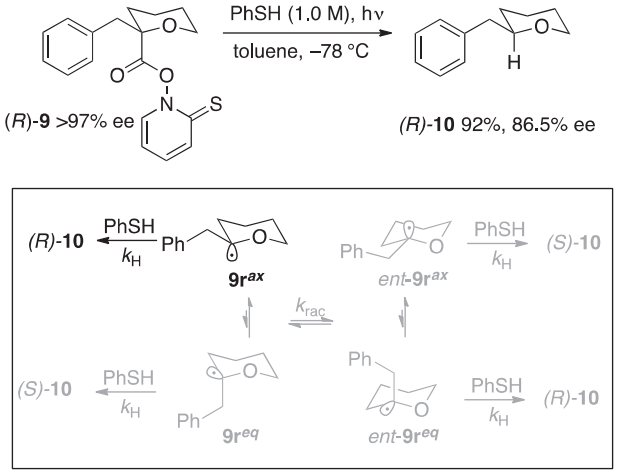
In 1998, Rychnovsky and coworkers examined the radical-mediated reductive decyanation of 2-cyanotetrahydropyrans [30]. When the tetrahydropyran derivative **4** was treated with dissolved lithium in ammonia at low temperature, the reduced product **5** was obtained with partial retention of the relative configuration (Scheme 2). This observation can be rationalized by a rapid stereoselective reduction of the radical **4r** to the axial organolithium species that is faster than the chair-chair interconversion which has an energy barrier of approximately 10 kcal mol^{-1}. The radicals ax-**4r** and eq-**4r** derived from ax-**4** and eq-**4** are expected to be rapidly equilibrating pairs of σ-radicals lying preferentially in the axial conformations ax-$\mathbf{4r^{ax}}$ and eq-$\mathbf{4r^{ax}}$ due to a stabilizing anomeric effect [31]. The axial radicals ax-$\mathbf{4r^{ax}}$ and eq-$\mathbf{4r^{ax}}$ are then rapidly converted to the corresponding configurationally stable axial organolithium species and, after protonation to *cis*-**5** and *trans*-**5**, respectively. It is important to notice that in this case the retention of configuration is not caused, as in the case of the 1-flurocyclopropyl radical, by a slow epimerization of the radical center but rather by a slow ring flip of the tetrahydropyran. The chirality is conserved by the conformation of the six-membered ring.



Scheme 2. MoC in decyanation reaction involving tetrahydropyranyl radicals (major reaction pathways depicted in black).



Scheme 3. Cyclization of a α-cyanotetrahydropyran derivative.



Scheme 4. MoC in the decarboxylation of a tetrahydropyran-2-carboxylic acid derivative (major reaction pathway depicted in black, $k_H \times [PhSH] > k_{rac}$).

This strategy was applied to the cyclization reaction of the enantiomerically pure nitrile **6** to the spirocyclic compound **7** in 65% yield and 42% ee (Scheme 3). The reductive lithiation was performed with lithium di-*tert*-butyl-biphenylide (LiDBB) at −78 °C [32]. Under these conditions, the intermediate radical **6r** was converted to the conformationally stable organolithium **8** faster than chair-chair interconversion. The axial organolithium intermediate **8** undergoes a carbometallation reaction before it is trapped with CO_2 and esterified with diazomethane.

The MoC in such system is not limited to processes involving reductive lithiation. Decarboxylation of a Barton ester has been shown to proceed with a good level of conservation of enantiomeric excess when a fast radical trap such thiophenol is used [33]. Irradiation of ester *(R)*-**9** in the presence of thiophenol gave the decarboxylated 2-benzyltetrahydropyran *(R)*-**10** in 92% yield and 86.5% ee at −78 °C (Scheme 4). This result is possible because (1) the starting Barton ester exists in one single chair conformation (axial ester group); (2) the chair-chair interconversion is slow at the temperature of the reaction (−78 °C, energy barrier of ca. 10 kcal mol^{-1}) relative to the hydrogen transfer; (3) as a consequence of an anomeric effect, radical **9r** exists almost exclusively in its axial form **9r^{ax}**; (4) both radicals **9r^{ax}** and **9r^{eq}** are expected to react at approximately the same rate from the front lobe, therefore hydrogen

transfer leading to (*R*)-**10** represents the major pathway of the reaction [31]. The racemization of radical **9r** generated from *(R)*-**9** can be used as a fast radical clock reaction, with an estimated rate $k_{rac} = 5.7 \times 10^8\ s^{-1}$ at 22 °C.

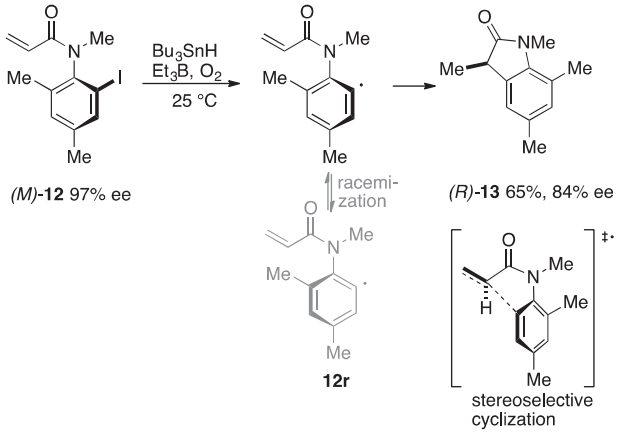
Dalgard and Rychnovsky reported another example of memory of chirality where the chiral information is preserved by the conformation of the radical intermediate and not the radical center [34]. Irradiation of the mixed oxalate of cyclodecenol **11** (89% ee) afforded the product of transannular cyclization with 26% ee (88% yield) at 23 °C and with 68% ee (51% yield) at −15 °C (Scheme 5). Further analysis of these results is difficult since the absolute configuration of the starting alcohol as well as of the product are not given. However, formation of the sp^2-hybridized secondary alkyl radical center in a cycle lying in a chiral conformation (tentatively depicted as **11r** in Scheme 5) that is slowly interconverting into its mirror image can explain the results.

Aryl radicals

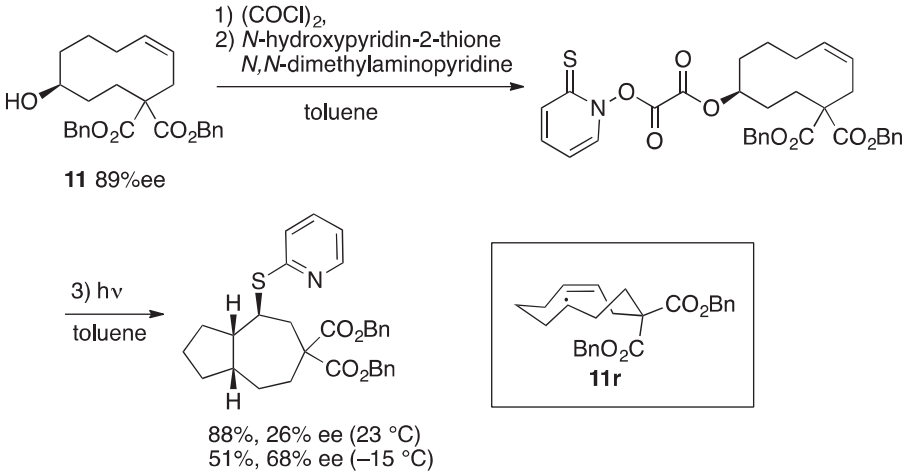
Curran et al. reported cyclization of acrylanilide derivatives to oxindoles [35]. In this reaction, an axial-to-central chirality is taking place [36]. Indeed, 2-iodo-6-methylanilide *(M)*-**12** (97% ee) exists as a stable atropisomer at room temperature and gives upon radical cyclization the oxindole *(R)*-**13** in 84% ee (Scheme 6). Although the racemization barrier of **12r** is expected to be low due the absence of the 2-iodo substituent that is necessary for atropisomerism, its rapid cyclization ensures a high enantioselectivity for the formation of oxindole (*R*)-**13**. The stereoselectivity of the cyclization is explained by the transition state depicted in Scheme 6. The formation of the minor enantiomer is either the result of a racemization of radical **12r** (in gray) or of a not perfectly selective radical cyclization process (attack of the radical on the other face of the olefin).

Similar results were obtained with axially chiral *N*-allyl amides [37,38] and carbamates [39] (Scheme 7). In this case, the model explaining the stereoselectivity of the cyclization differs from the one presented for the acrylamide in Scheme 6, since the alkene twists away from aryl radical due to the different positioning of the amide/carbamate bond [37,39]. The high level of MoC is rationalized by the very high rate constant for such cyclization processes ($k_{cycl} \geq 10^9\ M^{-1}\ s^{-1}$) [37].

The radical phosphanylation of similar aryl radicals was also reported to occur with a high level of MoC [40]. When the axially chiral 2-iodo-5-methylanilide *(P)*-**18** (92% ee) was treated with Me_3SnPPh_2, the aryl radical **18r** was trapped before racemization. After oxidative treatment, the axially chiral phosphine oxide *(P)*-**19** was obtained with complete retention of chirality (92% ee) (Scheme 8). This is the first example of MoC involving the conversion of an axially chiral starting material into another axially chiral product. The axial



Scheme 6. Cyclization of an axially chiral acrylamide.

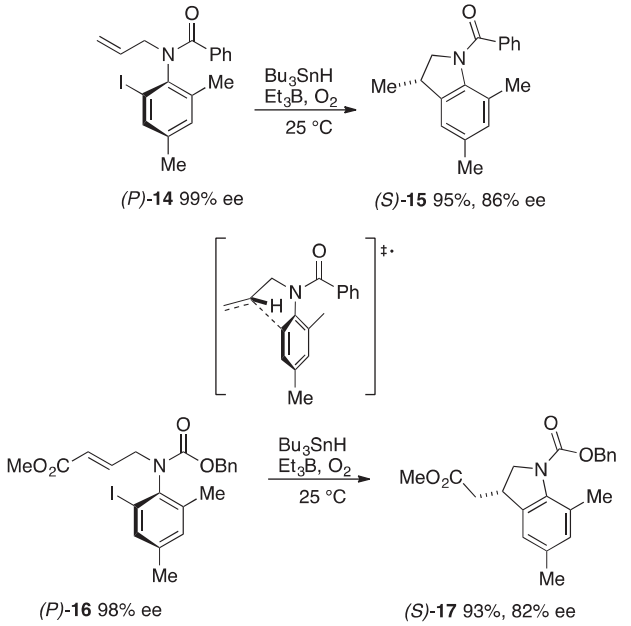


Scheme 5. MoC in a transannular cyclization.

chirality of the transient radical is preserved despite a strongly decreased energy barrier for its racemization relative to the starting iodide. A rate constant close to $10^9\,M^{-1}\,s^{-1}$ has been determined for the phosphanylation reaction that outperforms the racemization process (Scheme 8 in gray).

Acyclic ester and amide-substituted alkyl radicals

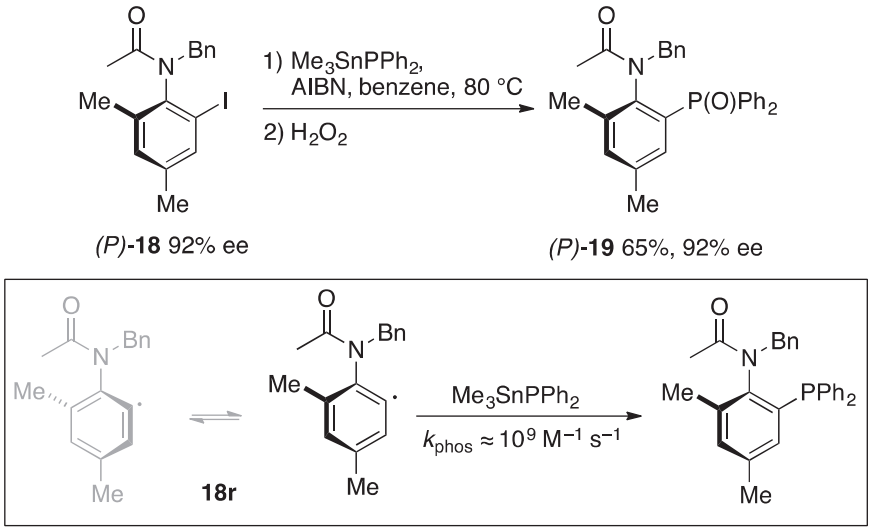
In 1967, Heiba and Dessau reported an intriguing radical addition–translocation–cyclization cascade with partial retention of optical rotation [11]. Treating the optically active ester **20** with benzoyl peroxide in carbon tetrachloride gave the lactone **21** (Scheme 9). Interestingly, the product was still optically active but the ratio of enantiomers was not reported. The reaction involves the addition of the trichloromethyl radical to the terminal alkyne followed by 1,5-hydrogen atom transfer, 5-*exo*-trig cyclization and a final fragmentation of a chlorine atom. Racemization of the intermediate radical, which possesses a transient chiral axis, involves a relatively small change of conformation and was expected to be fast. Curran and co-workers could confirm later that the small residual optical activity was not an artifact but they were unable to measure an enantiomeric excess for the product **21** [41]. To overcome analytical problems associated with lactone **21**, they modified the substrate to amide **22** (Scheme 10). Upon treatment of **22** with Bu_3SnH and azobisisobutyronitrile (AIBN), a mixture of two diastereomeric lactams was obtained in 38% yield. Both diastereomers showed the same enantiomeric excess of 68% ee showing that the axially chiral radical intermediate is cyclizing faster than racemizing (homofacial cyclization).



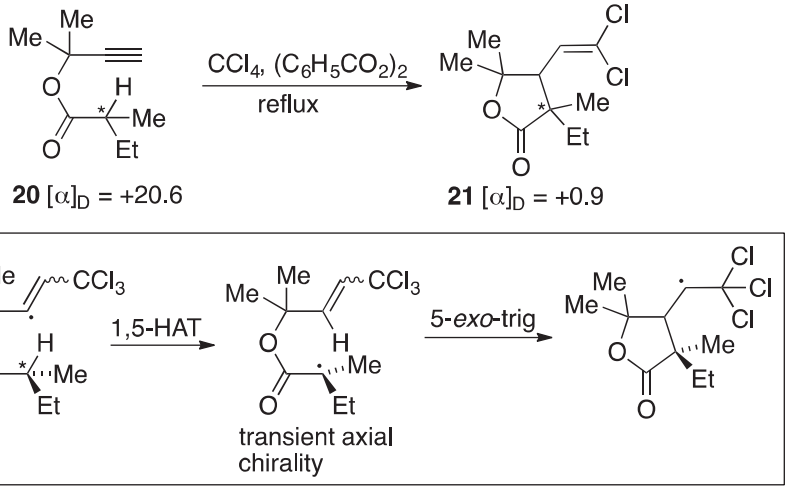
Scheme 7. Cyclization of axially chiral *N*-allyl amide and carbamate.

Benzylic radicals

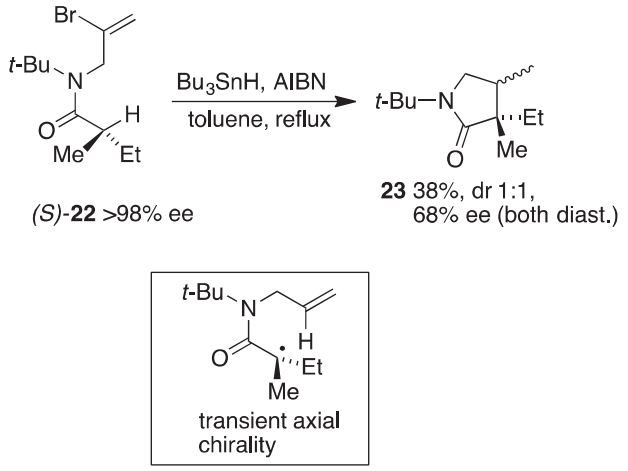
In 2001, Quirant, Bonjoch and coworkers reported that the radical cyclization of trichloroacetamide **24** afforded, beside the expected bicyclic lactam **25**, the unexpected byproduct **26** with complete inversion of stereochemistry at the benzylic center (Scheme 11) [42]. A similar result was observed when **24′**, the diastereomer of **24**, was used for this transformation.



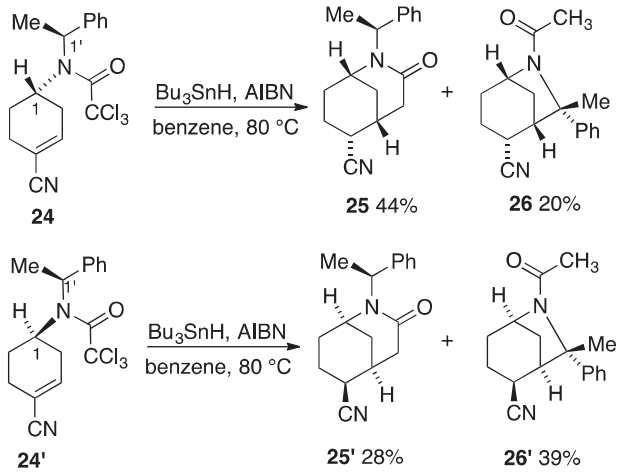
Scheme 8. Phosphanylation reaction converting an axially chiral substrate to an axially chiral product.



Scheme 9. Radical addition–translocation–cyclization process.



Scheme 10. Radical translocation-cyclization.



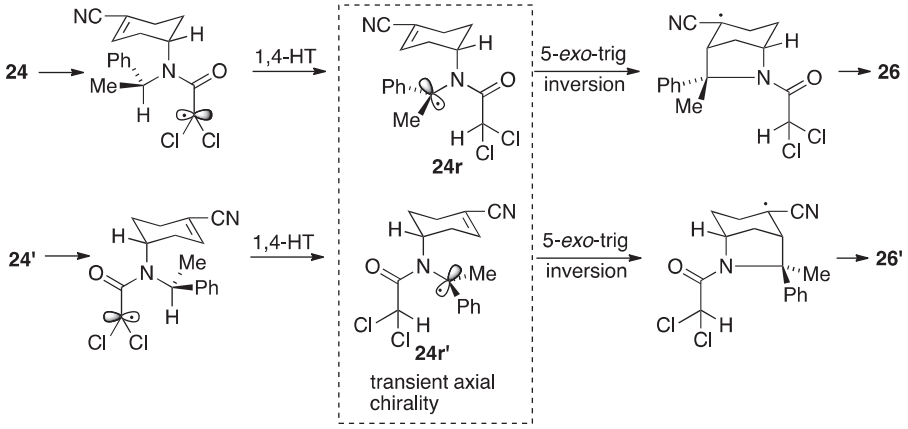
Scheme 11. Unexpected formation of acetamides via a translocation-cyclization pathway.

The reaction gave beside the expected **25′** the product of translocation-cyclization **26′** (Scheme 11).

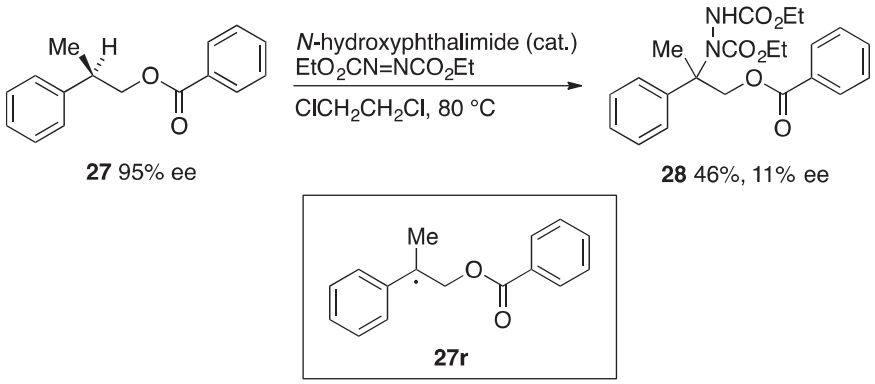
Acetamides **26** and **26′** are formed by a 1,4-hydrogen transfer and subsequent 5-*exo*-trig cyclization (Scheme 12). The fact that **26** and **26′** are diastereomers indicates that MoC is involved. Indeed, radical **24r** and **24r′** do not interconvert although their relative configuration differs only by the configuration of the transient chiral axis formed upon hydrogen atom abstraction at the benzylic position. Diaba, Bonjoch and coworkers have described more recently that similar MoC is also taking place when the reaction is performed under copper(I)-mediated chlorine atom transfer conditions [43]. To the best of our knowledge, these examples are the only reactions involving MoC in a radical process that is taking place in a heterofacial manner with inversion of the absolute configuration at the radical center. These results are well explained by the generation of the radical in a conformation that is perfectly organized for the subsequent heterofacial cyclization (Scheme 12).

Inoue and coworkers reported a surprising example of MoC in the intermolecular radical amination of a C(sp^3)–H bond with dialkyl azodicarboxylate mediated by *N*-hydroxyphthalimide (NHPI) [44]. The amination of the enantiomerically enriched **27** (95% ee) afforded the hydrazide **28** in 46% yield and 11% ee (Scheme 13). The origin of the partial retention of stereochemistry is so far not elucidated.

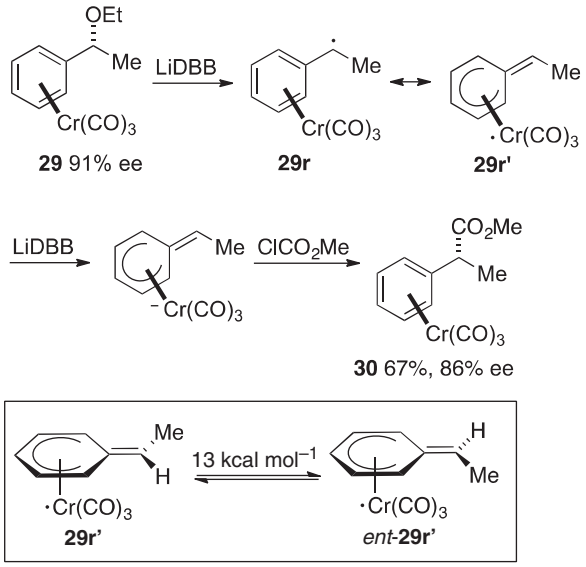
Schmalz, de Koning and coworkers have generated a $Cr(CO)_3$-complexed benzylic radical **29r** from the corresponding chiral benzylic ether **29** using lithium di-*tert*-butyl-biphenylide (LiDBB) [45]. This radical is better described as the 17 valence electron resonance structure **29r′** and it exhibits a significant configurational stability based on a calculated rotational



Scheme 12. Heterofacial mechanism in a translocation–cyclization reaction.



Scheme 13. Radical amination of a benzylic C(sp^3)–H bond.

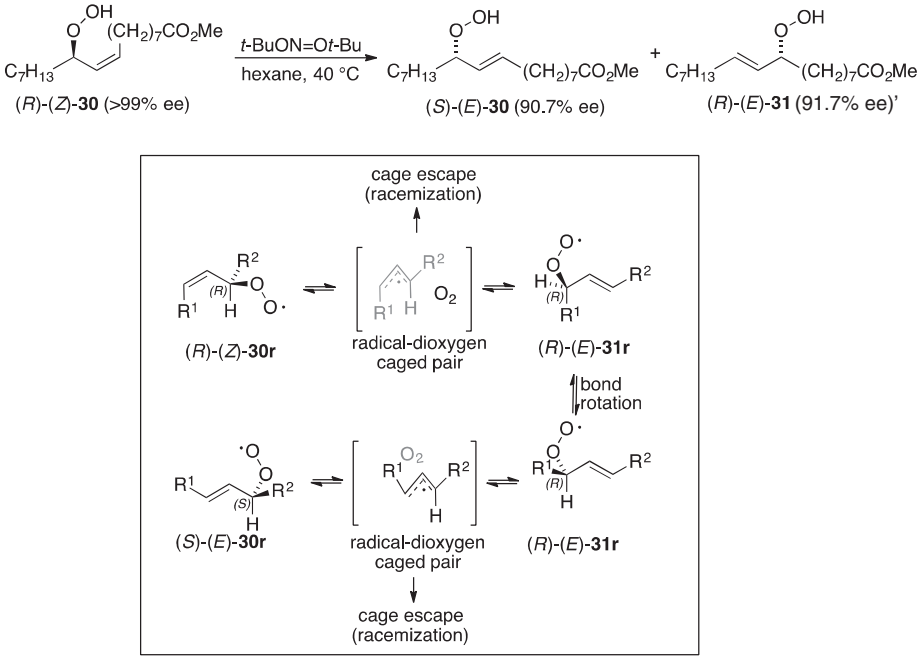


Scheme 14. Reaction involving $Cr(CO)_3$-complexed benzylic radicals.

barrier of 13.2 kcal mol^{-1}. This radical intermediate can be further reduced to the anion by a second equivalent of LiDBB and stereoselectively reacted with different electrophiles such as methyl chloroformate with a good overall level of retention enantiomeric purity (Scheme 14).

Allylic radicals

The stereochemical outcome of the [3,2] rearrangement of allylperoxyl radical has been investigated by Porter et al. [46]. They reported that the radical generated from methyl (*R*)-(*Z*)-11-hydroperoxyloleate (*R*)-(*Z*)-**30** afforded a mixture of (*S*)-(*E*)-**30** and (*R*)-(*E*)-**31** with high level of MoC. A β-fragmentation mechanism involving an intermediate allyl radical is supported by mechanistic investigations including the influence of solvent viscosity and isotopic labeling experiments. The initially generated peroxyl radical (*R*)-(*Z*)-**30r** fragments to form an allyl radical–dioxygen caged pair that collapses to form (*R*)-(*E*)-**31r** at a rate comparable with that of diffusion with full memory of chirality. The rearranged peroxyl radical (*R*)-(*E*)-**31r** can, after a conformational change, further rearrange to give stereoselectively (*S*)-(*E*)-**30r**. Allyl radicals that diffuse in solution react with the oxygen from the solvent with loss of stereochemistry



Scheme 15. The [3,2] allylperoxyl rearrangement.

and are responsible for the observed erosion of ee's. Decreasing the reaction temperature and increasing the viscosity of the solvent are both slowing down the cage escape process and favor the MoC.

Conclusions

Except for some specific applications in the field of enolate alkylation, the MoC has been considered so far as a curiosity rather than as a real strategy for preparative asymmetric synthesis. In this short review, we have summarized the state of the art of MoC for radical reactions involving monoradicals. Due to the exceptional reactivity of radicals, examples of MoC are reported in reactions that are not only run at low temperature but also in reactions performed at room temperature and above. Reaction cascades involving MoC during difficult C–H activation steps have been developed. We strongly believe that further applications of this approach may lead in the near future to mechanistically interesting and synthetically useful transformations.

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Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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References

1. Kawabata T, Yahiro K, Fuji K. Memory of chirality: enantioselective alkylation reactions at an asymmetric carbon adjacent to a carbonyl group. J Am Chem Soc 1991;113:9694–9696.
2. Seebach D, Wasmuth D. Alkylierung von aminosäuren ohne verlust der optischen aktivität: α- und β-alkylierung eines asparaginsäure-derivates. Angew Chem 1981;93:1007–1008.
3. Leuchs H. Die stereochemische behandlung der keto-enol-frage. (Über Spirane IV). Chem Ber 1913;46:2435–2442.

4. Luche MJ, Marquet A, Snatzke G. Configuration absolue d'indanones-1 et tetralones-1 substituees en 2. Tetrahedron 1972;28:1677–1695.
5. Ronteix MJ, Marquet A. Retention d'activite optique lors de l'halogenation de cetones optiquement actives. Tetrahedron Lett 1966;7:5801–5806.
6. Jones WM. Pyrazolines. IV. On the mechanism of decomposition and conformational analyses of 2-pyrazolines 1. J Am Chem Soc 1960;82:3136–3137.
7. Rinehart KL, Van Auken TV. Light-induced decomposition of pyrazolines. An improved entry into the cyclopropane series. J Am Chem Soc 1960;82:5251.
8. Orban I, Schaffner K, Jeger O. On the photochemical cyclization of saturated ketones and aldehydes to cyclobutanols. J Am Chem Soc 1963;85:3033–3035.
9. Fuji K, Kawabata T. Memory of chirality – a new principle in enolate chemistry. Chem-Eur J 1998;4:373–376.
10. Matsumura Y, Shirakawa Y, Satoh Y, Umino M, Tanaka T, Maki T, Onomura O. First example of memory of chirality in carbenium ion chemistry. Org Lett 2000;2:1689–1691.
11. Heiba EAI, Dessau RM. Vinyl radical isomerization. II. A new free-radical synthesis of γ-lactones with retention of optical activity. J Am Chem Soc 1967;89:2238–2239.
12. Crich D, Shirai M, Brebion F, Rumthao S. Enantioselective alkene radical cations reactions. Tetrahedron 2006;62:6501–6518.
13. Zhao H, Hsu DC, Carlier PR. Memory of chirality: An emerging strategy for asymmetric synthesis. Synthesis 2005;(1):1–16. doi: 10.1055/s-2004-834931.
14. Alezra V, Kawabata T. Recent progress in memory of chirality (MOC): an advanced chiral pool. Synthesis 2016.
15. Mu Y, Zhu C, Shi Z. Memory of chirality (MOC) in intramolecular sp3 C-H Amination. Synlett 2016;27:486–492.
16. Cozzi F, Siegel JS. Chirony of stereochemical metaphors. Org Biomol Chem 2005;3:4296–4298.
17. Curran DP, Porter NA, Giese B. Stereochemistry of radical reactions: concepts, guidelines, and synthetic applications. Weinheim; New York: VCH; 1996.
18. Paddon-Row MN, Houk KN. Conformational dependence of the pyramidalization of alkyl radicals. J Phys Chem-US 1985;89:3771–3774.
19. Griller D, Ingold KU, Krusic PJ, Fischer H. On the configuration of the tert-butyl radical [2]. J Am Chem Soc 1978;100:6750–6752.
20. Ignaczak A. Comparative quantum study on tert-butyl radical and cation. J Theoret Comput Chem 2011;10:325–348.
21. El Blidi L, Nechab M, Vanthuyne N, Gastaldi S, Bertrand MP, Gil G. En route to (*S*)-selective chemoenzymatic dynamic kinetic resolution of aliphatic amines. One-pot KR/racemization/KR sequence leading to (*S*)-amides. J Org Chem 2009;74:2901–2903.
22. Walborsky HM. The cyclopropyl radical. Tetrahedron 1981;37:1625–1651.
23. Ando T, Yamanaka H, Namigata F, Funasaka W. Reduction of gem-halofluorocyclopropanes with tributyltin hydride. J Org Chem 1970;35:33–38.
24. Gawronska K, Gawronski J, Walborsky HM. Formation of a chiral 1-fluoro-2,2-diphenylcyclopropyl radical in the Barton decarboxylation reaction. J Org Chem 1991;56:2193–2197.
25. Walborsky HM, Collins PC. Cyclopropanes. XXXVIII. Effect of 1-substituents on the stereochemical stability of the cyclopropyl radical. J Org Chem 1976;41:940–946.
26. Walborsky HM, Aronoff MS. Cyclopropanes XXXIII. Reaction of lithium metal surfaces with optically active 1-halo-1-methyl-2,2-diphenylcyclopropane. J Organomet Chem 1973;51:55–75.
27. Walborsky HM, Aronoff MS. Cyclopropanes XIX. Reaction of lithium metal with optically active halides. J Organomet Chem 1965;4:418–420.
28. Walborsky HM, Johnson FP, Pierce JB. Cyclopropanes. XXIV. Sodium-liquid ammonia reduction of optically active cyclopropyl halides. J Am Chem Soc 1968;90:5222–5225.
29. Boche G, Schneider DR, Wintermayr H. Alternative pathways in the reactions of cyclopropyl halides with alkali metal naphthalenes. J Am Chem Soc 1980;102:5697–5699.
30. Buckmelter AJ, Powers JP, Rychnovsky SD. Nonequilibrium radical reductions. J Am Chem Soc 1998;120:5589–5590.
31. Giese B, Dupuis J. Anomeric effect of radicals. Tetrahedron Lett 1984;25:1349–1352.
32. Rychnovsky SD, Hata T, Kim AI, Buckmelter AJ. Use of a conformational radical clock for evaluating alkyllithium-mediated cyclization reactions. Org Lett 2001;3:807–810.
33. Buckmelter AJ, Kim AI, Rychnovsky SD. Conformational memory in enantioselective radical reductions and a new radical clock reaction. J Am Chem Soc 2000;122:9386–9390.
34. Dalgard JE, Rychnovsky SD. Memory of chirality in the transannular cyclization of cyclodecenyl radicals. Org Lett 2004;6:2713–2716.
35. Curran DP, Liu W, Chen CHT. Transfer of chirality in radical cyclizations. Cyclization of o- haloacrylanilides to oxindoles with transfer of axial chirality to a newly formed stereocenter. J Am Chem Soc 1999;121:11012–11013.
36. Campolo D, Gastaldi S, Roussel C, Bertrand MP, Nechab M. Axial-to-central chirality transfer in cyclization processes. Chem Soc Rev 2013;42:8434.
37. Curran DP, Chen CHT, Geib SJ, Lapierre AJB. Asymmetric radical cyclization reactions of axially chiral N-allyl-o-iodoanilides to form enantioenriched N-acyl dihydroindoles. Tetrahedron 2004;60:4413–4424.
38. Petit M, Geib SJ, Curran DP. Asymmetric reactions of axially chiral amides: use of removable ortho-substituents in radical cyclizations of *o*-iodoacrylanilides and *N*-allyl-*N*-*o*-iodoacrylamides. Tetrahedron 2004;60:7543–7552.
39. Guthrie DB, Curran DP. Asymmetric radical and anionic cyclizations of axially chiral carbamates. Org Lett 2009;11:249–251.
40. Bruch A, Ambrosius A, Fröhlich R, Studer A, Guthrie DB, Zhang H, Curran DP. Memory of axial chirality in aryl radical phosphanylations. J Am Chem Soc 2010;132:11452–11454.

41. Sasmal A, Taniguchi T, Wipf P, Curran DP. Memory of chirality in rebound cyclizations of α-amide radicals. Can J Chem 2013;91:1–5.
42. Quirante J, Diaba F, Vila X, Bonjoch J, Lago E, Molins E. An unexpected course in the 6-exo radical cyclizations of trichloroacetamides on changing the N-substituent from benzyl to α-methylbenzyl. Comptes Rendus de l'Academie des Sciences - Series IIc: Chemistry. 2001;4:513–521.
43. Diaba F, Montiel JA, Bonjoch J. Unusual rearrangement and dearomatization reactions in Cu(I)-catalyzed atom transfer radical cyclizations from N-(1-phenylethyl)trichloroacetamides. Tetrahedron 2013;69:4883–4889.
44. Amaoka Y, Kamijo S, Hoshikawa T, Inoue M. Radical amination of C(sp3)-H bonds using N-hydroxyphthalimide and dialkyl azodicarboxylate. J Org Chem 2012;77:9959–9969.
45. Schmalz HG, De Koning CB, Bernicke D, Siegel S, Pfletschinger A. Memory of chirality in electron transfer mediated benzylic umpolung reactions of arene - Cr(CO)3 complexes. Angew Chem Int Edit 1999;38:1620–1623.
46. Porter NA, Mills KA, Caldwell SE, Dubay GR. The mechanism of the [3,2] allylperoxyl rearrangement: a radical-dioxygen pair reaction that proceeds with stereochemical memory. J Am Chem Soc 1994;116:6697–6705.