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Asymmetric synthesis of (−)-naltrexone†

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(−)-Naltrexone, an opioid antagonist used extensively for the management of drug abuse, is derived from naturally occurring opioids. Herein, we report the first asymmetric synthesis of (−)-naltrexone that does not proceed through thebaine. The synthesis starts with simple, achiral precursors with catalytic enantioselective Sharpless dihydroxylation employed to introduce the stereogenic centers. A Rh(I)-catalyzed C–H alkenylation and torquoselective electrocyclization cascade provides the hexahydro isoquinoline bicyclic framework that serves as the precursor to the morphinan core. The acidic conditions used for Grewe cyclization not only provide the morphinan framework, but also cause a hydride shift resulting in the introduction of the C-6 oxo functionality present in (−)-naltrexone. The C-14 hydroxyl group is installed by an efficient two-step sequence of Pd-mediated ketone to enone dehydrogenation followed by C–H allylic oxidation using Cu(II) and O_2, a method that has not previously been reported either for the synthesis or semi-synthesis of opioids. The longest linear sequence is 17 steps, and because the stereogenic centers in the product rely on Sharpless asymmetric dihydroxylation, the route could be used to access either enantiomer of the natural product, which have disparate biological activities. The route also may be applicable to the preparation of opioid derivatives that could not be easily prepared from the more fully elaborated and densely functionalized opioid natural products that have traditionally served as the starting inputs.

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Introduction

(−)-Morphine (**1**) is one of the oldest and most extensively used analgesics which led it, along with its congeners (−)-codeine (**2**) and (−)-thebaine (**3**), to garner significant attention from numerous organic chemists as targets for synthesis (Fig. 1).[1] Extensive modifications to the naturally occurring opioids have also been investigated in endeavors to increase potency and *in vivo* efficacy and have led to the discovery of semi-synthetic opioids such as (−)-ketorfanol (**4**)[2] and the extensively prescribed (−)-oxycodone (**5**).[3] However, despite the medical importance of naturally occurring and semi-synthetic opioid agonists, undesired side effects such as addictive properties and the potential for fatal overdoses are enormous societal problems. Therefore, semi-synthetic opioid antagonists were developed to address these growing problems.[4] Naltrexone (**6**) was first patented in 1967 (ref. 5) and is currently an important treatment option for opioid abuse and alcohol dependence.[4] The C-14 hydroxyl and *N*-cyclopropylmethyl substituent are essential structural features that are important for (−)-naltrexone's potency and antagonistic properties.[4]

The prevalent commercial routes to (−)-naltrexone (**6**) employ the natural product (−)-thebaine (**3**) as the starting material. A number of strategies have been developed for exchange of the *N*-methyl for an *N*-cyclopropylmethyl group.[6]

Hudlicky has extensively investigated this step,[7] including a particularly efficient alkylation and demethylation sequence of the thebaine derivative oripavine to give **9** (Fig. 2).[7c] The dienol ether functionality present in (−)-thebaine allows for the straightforward introduction of the C-14 hydroxyl group by oxidative methods. For example, in Hudlicky's sequence, the dienol ether functionality in **9** was epoxidized followed by *in situ* oxirane ring opening to generate enone **10** followed by hydrogenation to give (−)-naltrexone (Fig. 2).[8] Rice has also reported a semi-synthesis of the (+)-enantiomer of naltrexone. His

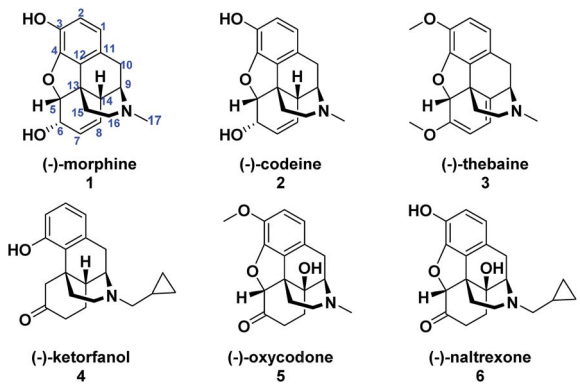

Fig. 1 Representative naturally occurring opioids (**1**–**3**) and semi-synthetic opioid agonists (**4**–**5**) and an antagonist (**6**).

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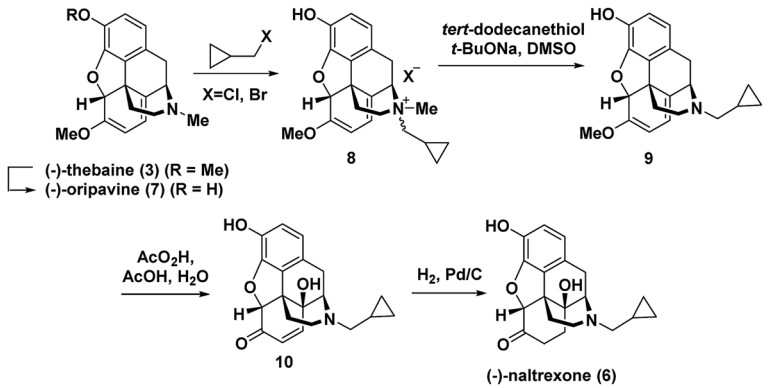
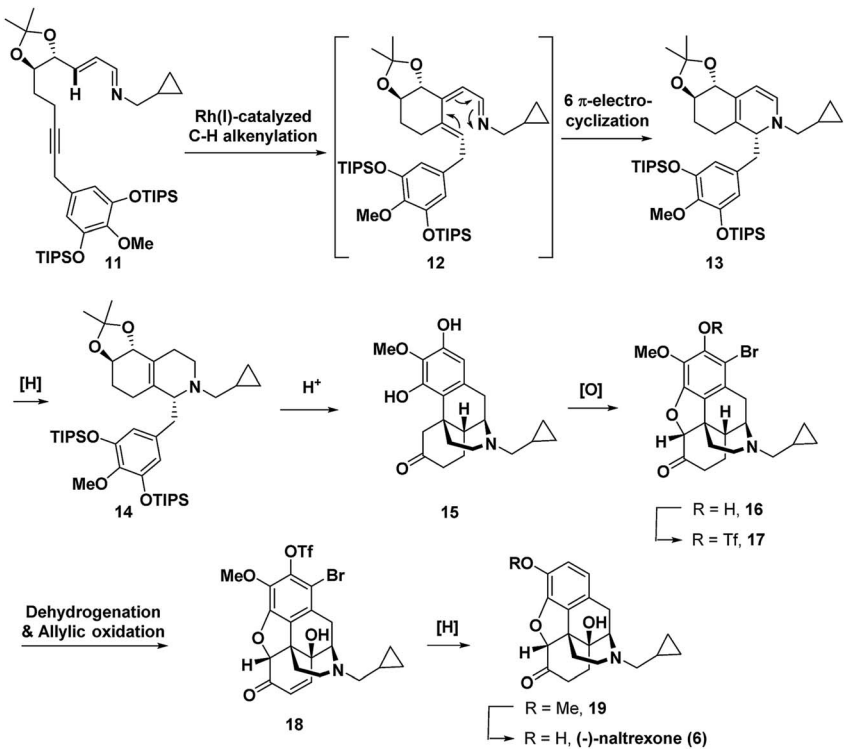


Fig. 2 Hudlicky's semi-synthesis of (−)-naltrexone.[7c]

synthesis proceeded through (+)-thebaine, which was prepared in five steps from the natural product (+)-sinomenine as an innovative starting material.[9]

(−)-Thebaine is currently isolated from opium poppies but is only a minor component of opium (0.3–1.5%), and poppy farming is problematic due to illicit drug activities.[10] An alternative synthetic route that bypasses (−)-thebaine and starts with commercially available achiral precursors would provide novel entry to (−)-naltrexone. Moreover, starting from simple inputs should enable the investigation of a variety of analogs not accessible from more fully elaborated and densely functionalized morphinan natural products like (−)-thebaine.[11]

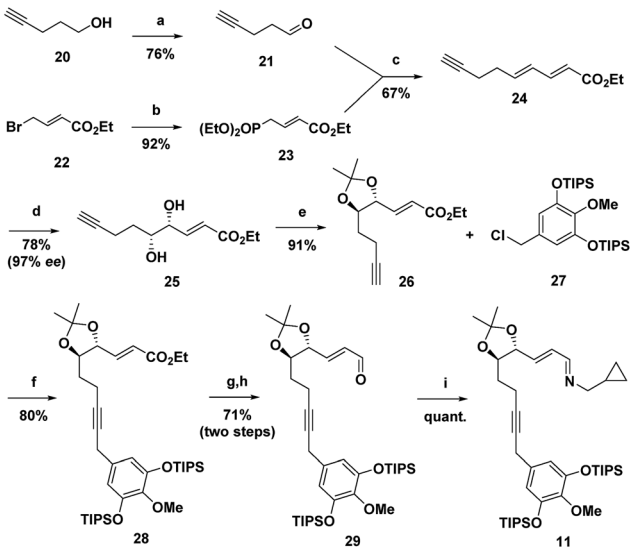
Recently, we reported the synthesis of the unnatural enantiomer of the opioid agonist (+)-ketorfanol (**4**) (Fig. 1) using a Rh(I)-catalysed C–H alkenylation and torquoselective 6-π electrocyclization cascade as a key step in the sequence.[12] Herein, we further apply this cascade approach to the synthesis of the considerably more complex opioid antagonist (−)-naltrexone (**6**) (Scheme 1). Imine **11** is efficiently prepared from achiral starting materials with catalytic asymmetric dihydroxylation used to introduce the stereogenic centers. Intramolecular Rh(I)-catalysed alkenylation to give azatriene **12** is followed by *in situ* torquoselective electrocyclization to set the desired stereochemistry in bicyclic hexahydroisoquinoline **13**, which is reduced to obtain **14** as a single diastereomer. Acid treatment provides the tetracyclic morphinan **15** by concomitant removal of the protecting groups, Grewe cyclization and redox neutral conversion of the diol to the desired keto group.



Scheme 1 Approach to (−)-naltrexone from simple, achiral precursors.

The 4-methoxy-3,5-disilyloxy substitution pattern on the phenyl ring of **14** was designed to allow for incorporation of the required aromatic ring oxygen substitution pattern while simultaneously ensuring that Grewe cyclization occurs without the possibility of generating regiosomeric products (*vide infra*).[1f] The pentacyclic ether **16** is then obtained from tetracyclic **15** by treatment with Br_2 in AcOH according to methods developed for the synthesis of codeine.[13]

For intermediate **16**, installation of the hydroxyl group at C-14 would most efficiently be accomplished by dehydrogenation to an enone followed by C–H γ-hydroxylation. However, in syntheses of morphinan natural products such as morphine and codeine, researchers have found that for the efficient dehydrogenation of 6-keto derivatives to enones the nitrogen must be protected by an electron withdrawing carbamoyl or sulphonamide rather than an *N*-alkyl group as is present in **16**.[1q,1u,14] Therefore, to enable dehydrogenation and γ-hydroxylation of **16** without the protection of the nitrogen, a Pd-mediated dehydrogenation method and Cu(II)-catalysed O_2-mediated allylic C–H oxidation conditions were developed. Alkene hydrogenation with concomitant reductive cleavage of both the triflate and the bromide in **18** gave **19**, which upon demethylation provided (−)-naltrexone in 17 steps for the longest linear sequence. Because the stereochemistry is set by asymmetric catalytic dihydroxylation, the same route could equally be employed to prepare the (+)-enantiomer of naltrexone, which has been reported to have antagonist activity toward Toll-like receptor 4.[15]

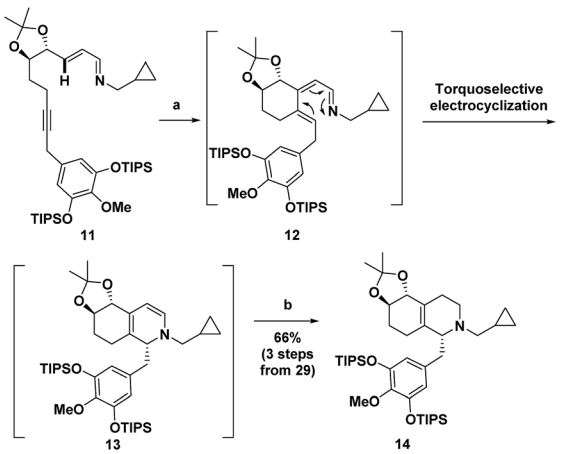


Scheme 2 Reactions and conditions: (a) $(COCl)_2$ (1.16 equiv.), DMSO (2.2 equiv.), Et_3N (5.0 equiv.), CH_2Cl_2, −78 → 23 °C; (b) $P(OEt)_3$, neat, 120 °C; (c) LiOH·H_2O (1.1 equiv.), MS 4 Å, THF, reflux; (d) K_2OsO_4·$2H_2O$ (1 mol%), $(DHQD)_2PHAL$ (5 mol%), $K_3Fe(CN)_6$ (3.00 equiv.), K_2CO_3 (3.00 equiv.), $MeSO_2NH_2$ (1.00 equiv.), tBuOH/H_2O, 0 °C; (e) 2,2-dimethoxypropane (10 equiv.), TsOH·H_2O (10 mol%), CH_2Cl_2, 0 °C; (f) $Pd(OAc)_2$ (5 mol%), XPhos (15 mol%), Cs_2CO_3 (1.5 equiv.), dioxane, 65 °C; (g) DIBAL (4.0 equiv.), THF, −78 °C; (h) DMP (1.75 equiv.), pyridine (6.0 equiv.), CH_2Cl_2, 0 °C; (i) cyclopropylmethylamine (1.2 equiv.), MS 3 Å, PhMe, 23 °C.

Results and discussion

The synthesis commenced with the preparation of imine **11** in seven steps from simple achiral starting materials (Scheme 2). Horner–Wadsworth–Emmons (HWE) reaction of aldehyde **21** and phosphonate **23** afforded **24** in 67% yield. Based upon a report by Takacs,[16] we found that use of LiOH as the base in the presence of 4 Å molecular sieves minimized competitive self-condensation of aldehyde **21** and thus provided the most robust and reproducible HWE reaction conditions particularly on larger scales. Highly regio- and enantioselective dihydroxylation with AD-mix-ß followed by protection of the diol as an acetonide gave **26** in high overall yield. The benzyl chloride **27**, which was coupled with alkyne **26**, was readily prepared in 75% overall yield from 4-*O*-methyl-3,5-dihydroxybenzoic acid, by silylation,[17] $LiAlH_4$ reduction to the benzyl alcohol,[1af] and chlorination with thionyl chloride. For the coupling of benzyl chloride **27** and alkyne **26**, the Cu-free conditions developed by Buchwald for the Heck alkynylation of benzyl chlorides proved to be the most effective approach.[18] Coupling product **28** was reliably obtained in good yield using $Pd(OAc)_2$ as the precatalyst and X-Phos as the ligand. DIBAL reduction of the ester followed by Dess–Martin periodinane (DMP) oxidation of the resulting alcohol gave aldehyde **29** in 71% overall yield. Condensation with cyclopropylmethylamine then provided **11**, which was taken on to the next step without purification.

Next, imine **11** was treated with 5 mol% of $[RhCl(coe)_2]_2$ precatalyst using $(pNMe_2)PhPEt_2$ as the ligand with heating in toluene to initiate the Rh(I)-catalysed cascade sequence. This process proceeds by Rh(I)-catalysed C–H activation followed by intramolecular insertion of the alkyne to give azatriene **12**, which *in situ* undergoes rapid electrocyclization to provide 1,2-dihydropyridine **13** (Scheme 3). This cascade process not only forms the desired bicyclic ring system, but also proceeds with high torquoselectivity as enforced by the isopropylidene protected diol to provide the desired diastereomer.[12] Without isolation, hexahydroisoquinoline **13** was reduced under mild



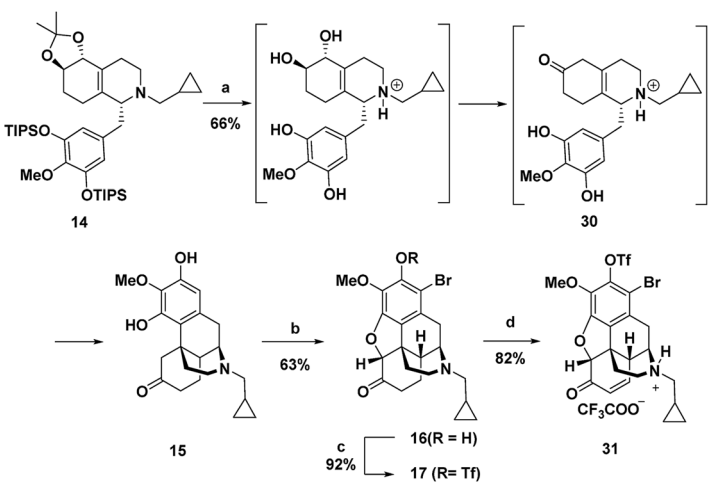
Scheme 3 Rh(I) C–H functionalization cascade. Condition and reagents: (a) $[RhCl(coe)_2]_2$ (5 mol%), $(pNMe_2)PhPEt_2$ (10 mol%), PhMe, 85 °C; (b) $NaBH(OAc)_3$ (5.0 equiv.), AcOH, EtOH, 0 °C.

conditions to give the octahydroisoquinoline **14** as a single stereoisomer in 66% overall yield from imine **11**.

Treatment of octahydroisoquinoline **14** with dilute H_3PO_4 and heat afforded morphinan **15** in 66% yield (Scheme 4). Acid treatment to provide morphinan **15** likely proceeds by removal of the silyl and acetonide protecting groups followed by *in situ* redox neutral conversion of the diol to the keto group *via* allylic alcohol ionization and a hydride shift to provide **30**, which then undergoes Grewe cyclization. Methods for α-bromination and subsequent nucleophilic displacement by an adjacent phenol as developed for the synthesis of codeine[13] gave the dihydrobenzofuran **16** in good overall yield. Two equivalents of Br_2 were needed because the first equivalent of Br_2 was very rapidly consumed by bromination of the highly electron-rich aromatic ring. Bromine substitution did not pose a problem because we anticipated that it could be removed with a global reduction step planned for later in the sequence (*vide infra*). Prior to installation of the C-14 hydroxyl, the free phenol in **16** was converted to the triflate in **17**,[17] which would also be removed in the reduction step.

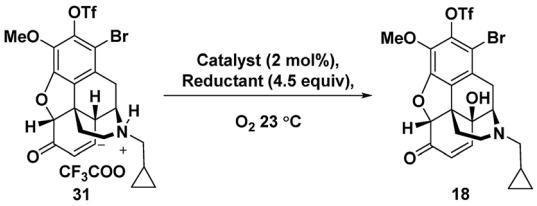
C-14 C–H hydroxylation of triflate **17** first required dehydrogenation to enone **31** in order to activate this site for γ oxidation (Scheme 4). Direct dehydrogenation has been reported to proceed with low yield for basic opioids with *N*-alkyl amine substituents.[14] To overcome this challenge in the synthesis of opioids, the amine is typically protected as a sulfonamide or carbamate,[1q,au,14] which then requires subsequent protecting group removal and installation of the *N*-alkyl group. Alternatively, more indirect, longer sequences have been developed to introduce this unsaturation.[19] We instead chose to investigate contemporary ketone dehydrogenation approaches that have been reported to be compatible with amine functionality. We first evaluated the IBX-MPO system, but the conversion of **17** to enone **31** was not observed.[20] Efficient, catalytic dehydrogenation methods utilizing $[Pd(allyl)_2Cl]_2$ with zinc amide bases have recently been reported,[21] but only partial conversion to enone **31** along with some allylation at the α-position occurred. Dehydrogenation with $Pd(TFA)_2$ in AcOH using O_2 as an external oxidant resulted in significant *N*-dealkylation.[22] This outcome is not surprising because Pd(II) catalysts under oxidizing conditions have been developed for the *N*-dealkylation of tertiary amines.[7a,23] However, by addition of trifluoroacetic acid to protect the amine as the corresponding salt, along with DMSO as a coordinating solvent to stabilize $Pd(TFA)_2$, complete conversion of ketone **17** was observed, with enone **31** isolated in 82% yield.

For the C-14 C–H hydroxylation of enone **31**, we looked for inspiration in prior semi-syntheses of oxycodone from morphine and codeine. Unfortunately, neither $Co(OAc)_3$ in acetic acid as reported by Rice[24] nor MnO_2 in $CHCl_3$ as reported by Sainsbury[25] resulted in C-14 hydroxylation of **31**. We next investigated a method reported for the direct C-14 C–H hydroxylation of codeinone by metal-catalysed peroxidation with O_2 followed by *in situ* reduction with sodium thiosulfate (entry 1, Table 1).[26] Disappointingly, no product was detected presumably because enone **31** is completely insoluble in the aqueous pH 8 buffer used as the solvent.[27] This led us to extensively explore organic co-solvents in combination with different oxidation catalysts and reductants. A large number of different co-solvents were first investigated, including DMF, THF, EtOH, DMSO and CH_3CN, but little to no product was detected. With pyridine as a 1 : 1 co-solvent with aqueous pH 8 buffer, enone **31** was highly soluble, and while some of the desired C–H hydroxylation product **18** was formed, extensive over-oxidation occurred as determined by LCMS (entry 2). However, by attenuating the basicity of the PBS buffer to pH 7, an improved yield of desired product **18** was obtained (entry 3). Under these conditions, $CuSO_4$ proved to be a superior oxidation catalyst than $KMnO_4$ (entry 4). Use of ketoglutaric acid instead of thiosulfate to reduce the peroxide intermediate was investigated for both $KMnO_4$ (entry 5) and $CuSO_4$ (entry 6). A significant improvement was observed for both catalysts with the highest yield obtained for $CuSO_4$ (entry 6). Finally, varying the ratio of pyridine to PBS buffer resulted in vast differences in reaction rate. While the use of pyridine without any aqueous co-solvent resulted in a slower rate, reaction progress could be more easily monitored and therefore the reaction could be reliably terminated before significant over-oxidation had occurred (entry 7).



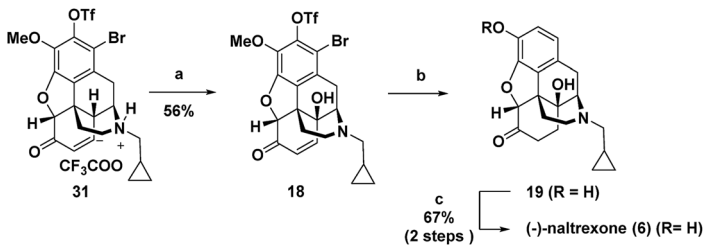
Scheme 4 Synthesis of dehydrogenated enone **31** as the precursor to Installation of C-14. Conditions and reagents: (a) 55% H_3PO_4, 125 °C; (b) Br_2 (2.0 equiv.), AcOH, 23 °C; $NaOH_{(aq)}$, 23 °C; (c) Tf_2O (3.3 equiv.), pyridine, 0 °C; (d) $Pd(TFA)_2$ (1.4 equiv.), TFA, DMSO, 80 °C.

Table 1 Optimization of γ-C–H hydroxylation of **31**



					NMR yield[e] (%)	
Entry	Catalyst[a] (2 mol%)	Reductant[b] (4.5 equiv.)	Solvent[c]	Time[d] (h)	sm(**31**)	pdt(**18**)
1	$KMnO_4$	$Na_2S_2O_3$	PBS pH 8	42	49	0
2	$KMnO_4$	$Na_2S_2O_3$	PBS pH 8/pyridine (1 : 1)	42	0	11
3	$KMnO_4$	$Na_2S_2O_3$	PBS pH 7/pyridine (1 : 1)	42	11	17
4	$CuSO_4$	$Na_2S_2O_3$	PBS pH 7/pyridine (1 : 1)	5	5	31
5	$KMnO_4$	Ketoglutaric acid	PBS pH 7/pyridine (1 : 1)	18	15	33
6	$CuSO_4$	Ketoglutaric acid	PBS pH 7/pyridine (1 : 1)	1.5	0	55
7	$CuSO_4$	Ketoglutaric acid	Pyridine	48	8	59

[a] Catalysts were added as 5 mM stock solutions in deionized H_2O. [b] Reductants were added as a 150 mM stock solution in deionized H_2O. [c] All solvents were sparged with O_2 prior to reaction. [d] The reaction was stopped when the product was at maximum yield as determined by LCMS exact ion count. [e] 1,3,5-Trimethoxybenzene was used as a standard for NMR yields. Remaining percent balance corresponds to unidentified overoxidized or degraded product.



Scheme 5 Installation of C-14 hydroxylation and endgame synthesis to (−)-naltrexone (**6**). Conditions and reagents: (a) $CuSO_4$ (2 mol%), ketoglutarate (4.5 equiv.), pyridine, 23 °C, O_2; (b) Et_3N (10 equiv.), $Pd(OH)_2$ (20 wt%), EtOAc : MeOH = 1 : 3, H_2, 23 °C; (c) BBr_3 (5 equiv.), CH_2Cl_2, −40 → 0 °C.

After γ-hydroxylation to afford **18**, we attempted to remove the aryl bromide and triflate as well as hydrogenate the enone to access **19** in a single step (Scheme 5). While formic acid with $Pd(PPh_3)_4$ only reductively cleaved the triflate and bromide, hydrogenation with H_2 and Pd/C reduced the double bond and achieved hydrodebromination but without reductive cleavage of the triflate. However, Pearlman's catalyst ($Pd(OH)_2$) under 1 atm of H_2 resulted in the complete reduction of the double bond along with the reductive removal of both the bromide and the triflate to give **19** in nearly quantitative yield.[28] For this reason, **19** was not purified but rather was directly submitted to final BBr_3 mediated demethylation, affording (−)-naltrexone **6** in 67% yield over the two steps.

Conclusions

We have developed a new approach for the synthesis of (−)-naltrexone in 17 linear steps. Starting with commercially available achiral substrates, a bicyclic hexahydroquinoline intermediate was accessed *via* a Rh(I)-catalyzed C–H alkenylation and torquoselective electrocyclization cascade. Grewe cyclization then provided the morphinan core with a concomitant hydride shift introducing the C-6 oxo functionality present in naltrexone. After formation of the dihydrobenzofuran, Pd-mediated dehydrogenation to the enone followed by allylic C–H oxidation using Cu(II) and O_2 introduced the C-14 hydroxyl group. This new route for the asymmetric synthesis of (−)-naltrexone from simple, achiral precursors could provide a means to prepare morphinan derivatives that would be difficult to access through semi-synthesis from opioid natural products.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Notes and references

1 For selected reviews and publications on total synthesis of opioids: (*a*) U. Rinner and T. Hudlicky, *Top. Curr. Chem.*, 2012, **309**, 33; (*b*) J. Zezula and T. Hudlicky, *Synlett*, 2005, 388; (*c*) M. Gates and G. Tschudi, *J. Am. Chem. Soc.*, 1952, **74**, 1109; (*d*) D. Elad and D. Ginsburg, *J. Am. Chem. Soc.*, 1954, **76**, 312; (*e*) R. Grewe and W. Friedrichsen, *Chem. Ber.*, 1967, **100**, 1550; (*f*) H. C. Beyerman, J. van Berkel, T. S. Lie, L. Maat, J. C. M. Wessels, H. H. Bosman, E. Buurman, E. J. M. Bijsterveld and H. J. M. Sinnige, *Recl. Trav. Chim. Pays-Bas*, 1978, **97**, 127; (*g*) K. C. Rice, *J. Org. Chem.*, 1980, **45**, 3135; (*h*) W. H. Moos, R. D. Gless and H. Rapoport, *J. Org. Chem.*, 1983, **48**, 227; (*i*) J. D. White, G. Caravatti, T. B. Kline, E. Edstrom, K. C. Rice and A. Brossi, *Tetrahedron*, 1983, **39**, 2393; (*j*) J. E. Toth, P. R. Hamann and P. L. Fuchs, *J. Org. Chem.*, 1988, **53**, 4694; (*k*) K. A. Parker and D. Fokas, *J. Am. Chem. Soc.*, 1992, **114**, 9688; (*l*) M. A. Tius and M. A. Kerr, *J. Am. Chem. Soc.*, 1992, **114**, 5959; (*m*) C. Y. Hong, N. Kado and L. E. Overman, *J. Am. Chem. Soc.*, 1993, **115**, 11028; (*n*) J. Mulzer, G. Dürner and D. Trauner, *Angew. Chem., Int. Ed.*, 1996, **35**, 2830; (*o*) J. D. White, P. Hrnciar and F. Stappenbeck, *J. Org. Chem.*, 1997, **62**, 5250; (*p*) G. Butora, T. Hudlicky, S. Fearnley, M. Stabile, A. Gum and D. Gonzales, *Synthesis*, 1998, 665; (*q*) D. F. Taber, T. D. Neubert and A. L. Rheingold, *J. Am. Chem. Soc.*, 2002, **124**, 12416; (*r*) B. M. Trost and W. Tang, *J. Am. Chem. Soc.*, 2002, **124**, 14542; (*s*) B. M. Trost, W. Tang and F. D. Toste, *J. Am. Chem. Soc.*, 2005, **127**, 14785; (*t*) K. A. Parker and D. Fokas, *J. Org. Chem.*, 2006, **71**, 449; (*u*) K. Uchida, S. Yokoshima, T. Kan and T. Fukuyama, *Org. Lett.*, 2006, **8**, 5311; (*v*) A. T. Omori, K. J. Finn, H. Leisch, R. J. Carroll and T. Hudlicky, *Synlett*, 2007, 2859; (*w*) H. Tanimoto, R. Saito and N. Chida, *Tetrahedron Lett.*, 2008, **49**, 358; (*x*) M. Varin, E. Barré, B. Iorga and C. Guillou, *Chem.–Eur. J.*, 2008, **14**, 6606; (*y*) H. Leisch, A. T. Omori, K. J. Finn, J. Gilmet, T. Bissett, D. Ilceski and T. Hudlicky, *Tetrahedron*, 2009, **65**, 9862; (*z*) P. Magnus, N. Sane, B. P. Fauber and V. Lynch, *J. Am. Chem. Soc.*, 2009, **131**, 16045; (*aa*) G. Stork, A. Yamashita, J. Adams, G. R. Schulte, R. Chesworth, Y. Miyazaki and J. J. Farmer, *J. Am. Chem. Soc.*, 2009, **131**, 11402; (*ab*) H. Koizumi, S. Yokoshima and T. Fukuyama, *Chem.–Asian J.*, 2010, **5**, 2192; (*ac*) T. Erhard, G. Ehrlich and P. Metz, *Angew. Chem., Int. Ed.*, 2011, **50**, 3892; (*ad*) V. Varghese and T. Hudlicky, *Synlett*, 2013, 369; (*ae*) J. Li, G.-L. Liu, X.-H. Zhao, J.-Y. Du, H. Qu, W.-D. Chu, M. Ding, C.-Y. Jin, M.-X. Wei and C.-A. Fan, *Chem.–Asian J.*, 2013, **8**, 1105; (*af*) M. Geffe and T. Opatz, *Org. Lett.*, 2014, **16**, 5282; (*ag*) M. Tissot, R. J. Phipps, C. Lucas, R. M. Leon, R. D. M. Pace, T. Ngouansavanh and M. J. Gaunt, *Angew. Chem., Int. Ed.*, 2014, **53**, 13498; (*ah*) L. Rycek, J. J. Hayward, M. A. Latif, J. Tanko, R. Simionescu and T. Hudlicky, *J. Org. Chem.*, 2016, **81**, 10930; (*ai*) K. H. Park, R. Chen and D. Y.-K. Chen, *Chem. Sci.*, 2017, **8**, 7031.

2 A. Manmade, H. C. Dalzell, J. F. Howes and R. K. Razdan, *J. Med. Chem.*, 1981, **24**, 1437.

3 (*a*) E. Falk, *Muench. Med. Wochenschr.*, 1917, **20**, 381; (*b*) E. Kalso, *J. Pain Symptom Manage.*, 2005, **29**, 47.

4 V. Varghese and T. Hudlicky, A Short History of the Discovery and Development of Naltrexone and Other Derivatives, in *Natural Products in Medicinal Chemistry*, ed. S. Hanessian, Wiley-VCH, Weinheim, 2014, ch. 6, pp. 225–250.

5 H. Blumberg, I. J. Pachter and Z. Matossian, *US Pat.*, 1967, vol. 3, pp. 332–950.

6 For examples of *N*-demethylation of opioids: (*a*) J. von Braun, *Ber. Dtsch. Chem. Ges.*, 1900, **33**, 1438; (*b*) K. C. Rice, *J. Org. Chem.*, 1975, **40**, 1850; (*c*) K. C. Rice and E. L. May, *J. Heterocycl. Chem.*, 1977, **14**, 665; (*d*) J. H. Cooley and E. J. Evain, *Synthesis*, 1989, **1**, 1; (*e*) R. A. Olofson, J. T. Martz, J. P. Senet, M. Piteau and T. Malfroot, *J. Org. Chem.*, 1984, **49**, 2081; (*f*) A. Coop, J. W. Janetka, J. W. Lewis and K. C. Rice, *J. Org. Chem.*, 1998, **63**, 4392; (*g*) K. McCamley, J. A. Ripper, R. D. Singer and P. J. Scammells, *J. Org. Chem.*, 2003, **68**, 9847; (*h*) G. Kok, T. D. Asten and P. J. Scammells, *Adv. Synth. Catal.*, 2009, **351**, 283; (*i*) Z. Dong and P. J. Scammells, *J. Org. Chem.*, 2007, **72**, 9881; (*j*) G. B. Kok, C. C. Pye, R. D. Singer and P. J. Scammells, *J. Org. Chem.*, 2010, **75**, 4806; (*k*) G. B. Kok and P. J. Scammells, *Bioorg. Med. Chem. Lett.*, 2010, **20**, 4499; (*l*) L. Werner, A. Machara, D. R. Adams, D. P. Cox and T. Hudlicky, *J. Org. Chem.*, 2011, **76**, 4628.

7 For semi-synthesis of naltrexone *via* oxymorphone or oripavine: (*a*) A. Machara, D. P. Cox and T. Hudlicky, *Adv. Synth. Catal.*, 2012, **354**, 2713; (*b*) M. A. Endoma-Arias, D. P. Cox and T. Hudlicky, *Adv. Synth. Catal.*, 2013, **355**, 1869; (*c*) A. Machara, L. Werner, H. Leisch, R. J. Carroll, D. R. Adams, D. Mohammad Haque, D. P. Cox and T. Hudlicky, *Synlett*, 2015, 2101.

8 For examples of the conversion of thebaine to opioids containing the C-14 hydroxyl group: (*a*) M. Freund and E. Speyer, *J. Prakt. Chem.*, 1916, **94**, 135; (*b*) F. H. Hauser, T.-K. Chen and F. I. Carroll, *J. Med. Chem.*, 1974, **17**, 1117; (*c*) I. Iijima, K. C. Rice and A. Brossi, *Helv. Chim. Acta*, 1977, **60**, 2135; (*d*) R. Krassnig, C. Hederer and H. Schmidhammer, *Arch. Pharm.*, 1996, **329**, 325; (*e*) D. Lopez, E. Quinoa and R. Riguera, *Tetrahedron Lett.*, 1994, **35**, 5727; (*f*) G. B. Kok and P. J. Scammells, *RSC Adv.*, 2012, **2**, 11318.

9 (*a*) I. Iijima, J. Minamikawa, A. E. Jacobson, A. Brossi and K. C. Rice, *J. Med. Chem.*, 1978, **21**, 398; (*b*) B. R. Selfridge, X. Wang, Y. Zhang, H. Yin, P. M. Grace, L. R. Watkins, A. E. Jacobson and K. C. Rice, *J. Med. Chem.*, 2015, **58**, 5038.

10 United Nations, *World Drug Report 2018, Analysis of Drug Markets, Opiates, Cocaine, Cannabis, Synthetic Drugs*, United Nations Publication, 2018, booklet 3.

11 The synthesis of (−)-oxycodone, a semi-synthetic opioid agonist, from simple commercially available precursors has been reported: A. Kimishima, H. Umihara, A. Mizoguchi, S. Yokoshima and T. Fukuyama, *Org. Lett.*, 2014, **16**, 6244.

12 E. M. Phillips, T. Mesganaw, A. Patel, S. Duttwyler, B. Q. Mercado, K. N. Houk and J. A. Ellman, *Angew. Chem., Int. Ed.*, 2015, **54**, 12044.
13 D. D. Weller and H. Rapoport, *J. Med. Chem.*, 1976, **19**, 1171.
14 I. Iijima and K. C. Rice, *Heterocycles*, 1977, **6**, 1157.
15 (*a*) M. R. Hutchinson, Y. Zhang, K. Brown, B. D. Coats, M. Shridhar, P. W. Sholar, S. J. Patel, N. Y. Crysdale, J. A. Harrison, S. F. Maier, K. C. Rice and L. R. Watkins, *Eur. J. Neurosci.*, 2008, **28**, 20; (*b*) X. Wang, Y. Zhang, Y. Peng, M. R. Hutchinson, K. C. Rice, H. Yin and L. R. Watkins, *Br. J. Pharmacol.*, 2016, **173**, 856.
16 J. M. Takacs, M. R. Jaber, F. Clement and C. Walters, *J. Org. Chem.*, 1998, **63**, 6757.
17 M. Node, S. Kodama, Y. Hamashima, T. Katoh, K. Nishide and T. Kajimoto, *Chem. Pharm. Bull.*, 2006, **54**, 1662.
18 C. H. Larsen, K. W. Anderson, R. E. Tundel and S. L. Buchwald, *Synlett*, 2006, 2941.
19 For examples of introducing unsaturation with basic opioids *via* ketal protection: (*a*) D. Passarella, A. Consonni, A. Giardini, G. Lesma and A. Silvani, *Bioorg. Med. Chem. Lett.*, 2002, **12**, 1981; (*b*) See ref. 13.
20 K. C. Nicolaou, T. Montagnon and P. S. Baran, *Angew. Chem., Int. Ed.*, 2002, **41**, 993.
21 D. Huang, Y. Zhao and T. R. Newhouse, *Org. Lett.*, 2018, **20**, 684.
22 T. Diao and S. S. Stahl, *J. Am. Chem. Soc.*, 2011, **133**, 14566.
23 B. Gutmann, P. Elsner, D. P. Cox, U. Weigl, D. M. Roberge and C. O. Kappe, *ACS Sustainable Chem. Eng.*, 2016, **4**, 6048.
24 A. Coop and K. C. Rice, *Tetrahedron*, 1999, **55**, 11429.
25 A. Ninan and M. Sainsbury, *Tetrahedron*, 1992, **48**, 6709.
26 Q. Zhang, J. O. Rich, I. C. Cotterill, D. P. Pantaleone and P. C. Michels, *J. Am. Chem. Soc.*, 2005, **127**, 7286.
27 Intermediate **31** is much more hydrophobic and less soluble in aqueous solution than codeinone.
28 A. P. Kozikowski, W. Tuckmantel and C. George, *J. Org. Chem.*, 2000, **65**, 5371.