C7β-Methyl Analogues of the Orvinols: The Discovery of Kappa Opioid Antagonists with Nociceptin/Orphanin FQ Peptide (NOP) Receptor Partial Agonism and Low, or Zero, Efficacy at Mu Opioid Receptors

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‡Department of Pharmacology, University of Michigan, Ann Arbor, Michigan 48109, United States

ABSTRACT: Buprenorphine is a successful analgesic and treatment for opioid abuse, with both activities relying on its partial agonist activity at mu opioid receptors. However, there is substantial interest in its activities at the kappa opioid and nociceptin/orphanin FQ peptide receptors. This has led to an interest in developing compounds with a buprenorphine-like pharmacological profile but with lower efficacy at mu opioid receptors. The present article describes aryl ring analogues of buprenorphine in which the standard C20-methyl group has been moved to the C7β position, resulting in ligands with the desired profile. In particular, moving the methyl group has resulted in far more robust kappa opioid antagonist activity than seen in the standard orvinol series. Of the compounds synthesized, a number, including 15a, have a profile of interest for the development of drug abuse relapse prevention therapies or antidepressants and others (e.g., 8c), as analgesics with a reduced side-effect profile.

INTRODUCTION

Buprenorphine (1a, Chart 1) is widely used for the treatment of opioid abuse and as an analgesic. Its mu opioid receptor (MOPr) partial agonist character is of primary importance for both indications, but it is apparent that activity at other receptors, in particular, antagonism at the kappa opioid receptor (KOPr), may play an important role in its clinical utility.1

The very high rate of relapse to drug use after a period of abstinence is a major problem in substance abuse treatment, with ~70% of treated addicts relapsing within the first year following treatment.2 The fact that many drug users use more than one drug further complicates the situation. A variety of factors play a role in precipitating relapse, but stress and/or a priming dose of the drug are particular risks. In preclinical studies, inhibition or genetic ablation of KOPrs has been shown to inhibit stress-induced relapse, but this approach has not been effective in blocking drug-prime-induced reinstatement to drug-seeking behavior.3

In contrast to the studies using selective KOPr antagonists, our own preclinical findings4,5 suggest that a combination of buprenorphine and naltrexone can be effective in blocking drug-prime-induced reinstatement to both cocaine- and opioid-seeking behavior. The combination acts as a KOP and delta opioid (DOP) receptor antagonist,6 a lower potency nociceptin/orphanin FQ peptide (NOP) receptor partial agonist,7 and a MOP antagonist.

Encouraging results have also been observed in two small clinical trials using a buprenorphine and naltrexone combination therapy in a ratio that should block most, or all, of buprenorphine’s MOPr agonist activity.8,9 The combination proved to be effective in reducing relapse in recovering opiate addicts and also caused a significant reduction in cocaine use. The beneficial effect on cocaine use is being more thoroughly evaluated within The National Drug Abuse Treatment Clinical Trials Network in the Cocaine Use Reduction with Buprenorphine (CURB: CTN-0048) study.

Thus, preclinical and clinical data suggest that the buprenorphine–naltrexone combination has significant therapeutic potential for the treatment of relapse and polydrug addiction, but it has substantial issues that need to be resolved. First, delivery of the combination is problematic; buprenorphine has poor oral bioavailability and is given sublingually, whereas naltrexone is active after oral administration but much less so after sublingual administration. The two compounds are

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for buprenorphine al. found no evidence for activation of NOPr being important for bifunctional ligands with low efficacy at NOPr (equivalent to buprenorphine) and appearing to be efficacious at MOPr and KOPr. However, we recently reported on a series of aryl analogues of buprenorphine, some of which displayed pharmacological properties directed for illicit, nonmedical use. Second, the exact nature of this diastereoselectivity is not clear. There has been speculation that methacrolene should give a more favorable distribution of product due to the increased bulk of the aldehyde, but it has been reported that methacrolene does not undergo Diels–Alder reaction with thebaine and N-cyclopropylcarbonylnorthebaine, but it gives the C7α-methyl adduct (3, Chart 1), the opposite to that desired and a result of the methyl group being bulkier than the nitrile. Methacrolene should give a more favorable distribution of product due to the increased bulk of the aldehyde, but it has been reported that methacrolene does not undergo Diels–Alder reaction with thebaine. We have previously shown that lithium tetrafluoroborate catalyzes Diels–Alder reactions between N-cyclopropylcarbonylnorthebaine and cycloalkenones and have now applied this method to the reaction with methacrolene (Scheme 1). The reaction was successful, giving a 1.4:1 mixture of the C7α-methyl (4a) and C7β-methyl (4b) adducts that could be separated by silica gel chromatography. Addition of phenyl Grignard, in the presence of tetrabutylammonium fluoride, to 4b gave the secondary alcohol 5a, with opposite stereochemistry at C20 to that desired. This bias toward the S-isomer (5a) parallels our findings on Grignard addition to the aldehyde of the related C7β-H series and is opposite to that observed on addition of Grignard reagent to the methyl ketone in the C7β-H series. Treatment of 5a with LiAlH4 to reduce the amide before 3-O-demethylation gave 10a. To obtain the desired diastereoisomer, 5a was oxidized to the phenyl ketone (6a) before LiAlH4 reduction of both the cyclopropylcarbonyl group and the ketone, the latter occurring stereoselectively, to give 7a. 3-O-Demethylation yielded 8a. The analogues (8b–8e; 10b–10e) were prepared in an identical manner. The 4-fluoro analogues (7e, 9e) were not fully stable to propanethiol-mediated 3-O-demethylation, which, in the case of 7e, resulted in the formation of isolable amounts of 8f where the fluoro substituent was substituted by propanethiol.

The etheno-bridged aldehyde 4b was also hydrogenated to 11, and the same sequence of steps was carried out to provide the ethano-bridged analogues 15 and 17.

### RESULTS

In order to streamline the development process and avoid unnecessary full evaluation of ligands of limited interest to this project, the compounds were screened in a [35S]GTPγS assay for MOPr, KOPr, and NOPr efficacy at a very high concentration (10 μM) to determine peak efficacy at each receptor (Table 1). Potencies as agonists (EC50) or antagonists (Kᵢ) were then determined for the most interesting compounds (chosen based on efficacies at the receptors and their fit with the target profiles) and reported in Table 1. A range of compounds were also evaluated for affinity at MOP, DOP, and NOP receptors by measuring displacement of [3H]-diprenorphine binding from membranes of C6-rat glioma
cells expressing recombinant rat MOPr and DOPr and CHO cells expressing recombinant human KOPr (Table 2). NOPr binding affinity was measured by displacement of \(^{[3H]}\)nociceptin from membranes of HEK cells expressing recombinant NOPr. Details of these assays have been described previously.6,21−24

All ligands from series 8 are KOPr antagonists with maximal percent stimulation <10%. Efficacy at MOPr ranges from zero (8a) to moderate efficacy partial agonism (8d, 8f: 35 and 49% of DAMGO, respectively) with clear SAR relating to the location of the phenyl ring substituent (4′ > 3′ > 2′). At NOPr, the compounds were partial agonists somewhat similar in efficacy to buprenorphine, with the highest efficacy demonstrated by the unsubstituted (8a; 56%), 3′-methyl substituted (8c; 43%), and 4′-fluoro (8e, 51%) analogues. Potency at NOPr was higher than seen with buprenorphine. Series 10, the diastereomers of 8, were consistently of higher efficacy at the KOPr with only the 4′-Me (10d) substituted analogue profiling as a KOPr antagonist. The others in the series were moderate to high efficacy KOPr agonists (45−92% of U69,593). At MOPr, they were all of moderate efficacy (33−55%) and very low efficacy at NOPr.

The phenyl and substituted phenyl, ethano-bridge analogues (15a−h) had very similar SAR to series 8 in that they also had very low, or no, efficacy at KOPr. A number (15a−e) were evaluated as antagonists at this receptor and were found to be as potent as buprenorphine (all having \(K_a < 1\) nM). As with series 8, they were also antagonists (e.g., 15a) or low-efficacy partial agonists at MOPr (≤17% of DAMGO). While SAR at this receptor was not absolutely clear cut, 4′-substituents again gave rise to higher efficacy than 3′-substituents (e.g., 15e vs 15h, 15d vs 15c). This series was extended to include heterocyclic analogues 15i−15m. Those having a thiophene ring (15i−15l) had partial agonist activity at KOPr (10−28%) and at MOPr (10−61%), whereas 15m, having a 3-furanyl group, was devoid of efficacy at KOPr and MOPr. Only 15m had appreciable efficacy at NOPr within the series of heterocyclic analogues.

\[\text{Scheme 1}^{\text{a}}\]

\[\text{a} \text{ (i) Methacrolein, LiBF}_4; \text{(ii) ArMgBr, Bu}_4\text{NBr, THF, reflux; (iii) LiAlH}_4\text{, THF; (iv) PrSNa, HMPA; (v) DMSO, oxalyl chloride, CH}_2\text{Cl}_2.\]

\[\text{Table 2}\]

\[\begin{array}{|c|c|}
\hline
\text{Compound} & \text{Affinity (nM)} \\
\hline
\text{8a} & \text{56} \\
\text{8c} & \text{43} \\
\text{8e} & \text{51} \\
\hline
\end{array}\]

\[\text{10d} & \text{55} \\
\hline
\end{array}\]

\[\text{4244}\]

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others had roughly equivalent affinity to that of buprenorphine (e.g., 8a, 8c, 15a, 15b, 15c).

In order to help explain the unusually low efficacy at KOPr of this series, the docking of 15a to the crystal structure of the KOPr was examined. The crystal structure of the KOPr was determined in the presence of the selective KOPr antagonist JDTic and presumably represents the inactive conformation of the receptor and, importantly, the conformation favored when binding 15a.25 15a sits in the hydrophobic binding pocket with the expected interaction between the protonated nitrogen and the side chain of Asp138, while the C7\β-methyl projects toward Tyr139 in TM3 (Figure 1).

**DISCUSSION**

Members of the orvinol series of compounds are mostly known for their nonselective binding to MOPr, KOPr, and DOPr and potent agonist activity at one or more of these receptors.26 Even those with a cyclopropylmethyl (CPM) group attached to the basic nitrogen, which has the effect of reducing efficacy particularly at MOPr,27 tend to be efficacious and potent agonists, primarily at KOPr.14 Buprenorphine, being a KOPr antagonist, is a very distinct member of the series, with the lack of efficacy at KOPr being attributed to the significant steric bulk adjacent to C20.14 Initially, it was believed that buprenorphine was also unusual in having measurable affinity for NOPr,28 an activity that has been postulated to explain some of buprenorphine’s in vivo pharmacology.29,30 However, in recent years, it has become apparent that some other members of the orvinol family also interact with NOPr, particularly those with a bulky group attached to C20 (the \(t\)-butyl group of buprenorphine fulfills this role).31−33 While it has been possible to introduce good affinity for NOPr, it has proven to be difficult to couple this with moderate efficacy for this receptor without also introducing efficacy for classical opioid receptors, in particular KOPr. The orvinol TH-030418 (18; Chart 1) is reported as having affinity for NOPr virtually equivalent to its affinity for MOPr, KOPr, and DOPr; however, it also displays very potent and efficacious antinociceptive activity in vivo. This activity is blocked by the opioid antagonist naltrexone, indicating high efficacy at MOPr and/or KOPr.33 Even more closely related to the current series are analogues of 1a having alternative bulky groups at C20.31 In that series, moderate affinity and efficacy for NOPr was always associated with partial agonism at MOPr and/or KOPr. The robust KOPr antagonist activity of series 8 and 15, especially when coupled with
KOPr25 allows a hypothesis to be formulated to explain the

Receptors (KOPr) and nociceptin (NOPr); values are an average

nM or antagonist

and Tyr139, up; i.e., through an interaction between the C7

whereas in the active conformation, they are much closer,

Tyr139 and the whole of TM3 move away from this position,

1b

with the recently reported

methyl group from C20 to the C7

improved affinity for NOPr, is therefore unprecedented within

the orvinols and close analogues. That they are 2° alcohols,

which typically have very much higher efficacy than their 3°

 analogues, 14 confirms the very substantial effect of moving

the methyl group from C20 to the C7β-position. A comparison

with the recently reported 1b and aryl substituted analogues

confirms the importance of this methyl group. 1b and

analogues differ from 15 only in the location of this single

methyl, yet in the 1b series, only the parent compound (R =

Ph) and the 3′-chloro analogue (1c: R = 3-CiPh) had low

efficacy at KOPr (19 and 26%, respectively), with other

substituents (2′-, 3′-, and 4′-methyl, 3′- and 4′-F) all resulting

in efficacy in the range 77–102% at this receptor. 15

Docking of 15a to the published crystal structure of the

KOPr, 25 allows a hypothesis to be formulated to explain the

very low efficacy of this series to the KOPr. In the model

of the KOPr active and inactive states, 25 the methyl group of 15a

projects toward Tyr139 in TM3. In the inactive conformation,

Tyr139 and the whole of TM3 move away from this position,

whereas in the active conformation, they are much closer,

possibly too close to allow the active conformation to be taken

up; i.e., through an interaction between the C7β-methyl group

and Tyr139, 15a and analogues may disfavor the active state of

the receptor.

Distinct SAR for affinity and efficacy at NOPr is found in

series 8 and 15. In both cases, the unsubstituted parent or a 3′-

substituent gives highest efficacy at NOPr, whereas highest

affinity is associated with a 4′-substituent, although this latter

effect is not large.

■ CONCLUSIONS

Moving the methyl group from C20 to the C7β position has

resulted in one of the most striking pieces of SAR in the orvinol

series. In particular, the robust reduction in efficacy at KOPr

coupled with a retention, or increase, in NOPr affinity and
efficacy has resulted in a series of compounds worthy of

consideration as (i) relapse prevention agents and (ii) low

abuse liability analgesics. 15a is currently undergoing in vivo

evaluation as part of its preclinical development.

■ EXPERIMENTAL SECTION

General Procedures. Reagents and solvents were purchased from

Sigma-Aldrich or Alfa Aesar and used as received. Buprenorphine (1a)

was supplied by the National Institute on Drug Abuse, Bethesda,

Maryland. 1H and 13C NMR spectra were obtained with a Bruker 400

MHz instrument (1H at 400 MHz, 13C at 100 MHz); δ is given in ppm,

J, in Hz, with TMS as an internal standard. ESI-MS: microTOF

(BRUKER), EIMS: Fisons Autosampler. Microanalysis: PerkinElmer

Table 1. Maximal Stimulation of [35S]GTPγS Binding of the New C7β-Methyl Orvinol Analogues to Opioid and NOP Receptors

<table>
<thead>
<tr>
<th></th>
<th>MOPr</th>
<th>KOPr</th>
<th>NOPr</th>
<th>DOPr</th>
</tr>
</thead>
<tbody>
<tr>
<td>[35S]GTPγS, % stimulation, &quot; and, in brackets, agonist EC50/nM or antagonist Kd/nM&quot;</td>
<td>[35S]GTPγS, % stimulation, &quot; and, in brackets, agonist EC50/nM or antagonist Kd/nM&quot;</td>
<td>[35S]GTPγS, % stimulation, &quot; and, in brackets, agonist EC50/nM or antagonist Kd/nM&quot;</td>
<td>[35S]GTPγS, % stimulation, &quot; and, in brackets, agonist EC50/nM or antagonist Kd/nM&quot;</td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>20 ± 6% (EC50: 0.7 ± 0.3 nM)</td>
<td>0 ± 6% (Kd = 0.14 ± 0.06 nM)</td>
<td>39 ± 12% (EC50: 1480 ± 980 nM)</td>
<td>7 ± 3%</td>
</tr>
<tr>
<td>1b</td>
<td>6.0 ± 1</td>
<td>19 ± 4</td>
<td>4 ± 4</td>
<td>14 ± 4</td>
</tr>
<tr>
<td>8a</td>
<td>48 ± 6%</td>
<td>3 ± 7%</td>
<td>56 ± 2.5% (EC50: 416 ± 74 nM)</td>
<td>7 ± 3%</td>
</tr>
<tr>
<td>8b</td>
<td>12 ± 5%</td>
<td>-4 ± 1%</td>
<td>17 ± 1%</td>
<td></td>
</tr>
<tr>
<td>8c</td>
<td>22 ± 5% (EC50: 1.4 ± 0.4 nM)</td>
<td>6 ± 2%</td>
<td>54 ± 11% (EC50: 14 ± 5 nM)</td>
<td>15 ± 3%</td>
</tr>
<tr>
<td>8d</td>
<td>35 ± 11% (EC50: 0.24 ± 0.04 nM)</td>
<td>-6 ± 1%</td>
<td>14 ± 2%</td>
<td></td>
</tr>
<tr>
<td>8e</td>
<td>26 ± 8% (EC50: 0.22 ± 0.06 nM)</td>
<td>9 ± 1%</td>
<td>51 ± 20% (EC50: 7.3 ± 3 nM)</td>
<td></td>
</tr>
<tr>
<td>8f</td>
<td>49 ± 2%</td>
<td>4 ± 10%</td>
<td>20 ± 4%</td>
<td></td>
</tr>
<tr>
<td>10a</td>
<td>33 ± 6%</td>
<td>62 ± 4%</td>
<td>5 ± 6%</td>
<td></td>
</tr>
<tr>
<td>10b</td>
<td>48 ± 1%</td>
<td>72 ± 4%</td>
<td>12 ± 2%</td>
<td></td>
</tr>
<tr>
<td>10c</td>
<td>40 ± 13%</td>
<td>92 ± 4%</td>
<td>11 ± 3%</td>
<td></td>
</tr>
<tr>
<td>10d</td>
<td>49 ± 3%</td>
<td>8 ± 5%</td>
<td>4 ± 5%</td>
<td></td>
</tr>
<tr>
<td>10e</td>
<td>55 ± 7%</td>
<td>45 ± 6%</td>
<td>7 ± 3%</td>
<td></td>
</tr>
<tr>
<td>15a</td>
<td>2 ± 4% (Kd = 0.28 ± 0.04 nM)</td>
<td>-2 ± 1% (Kd = 0.09 ± 0.04 nM)</td>
<td>56 ± 1% (EC50: 147 ± 33 nM)</td>
<td>0 ± 4%</td>
</tr>
<tr>
<td>15b</td>
<td>15 ± 7%</td>
<td>-4 ± 4% (Kd = 0.13 ± 0.05 nM)</td>
<td>15 ± 4%</td>
<td></td>
</tr>
<tr>
<td>15c</td>
<td>7 ± 1%</td>
<td>-1 ± 1% (Kd = 0.12 ± 0.08 nM)</td>
<td>61 ± 15% (EC50: 331 ± 223 nM)</td>
<td></td>
</tr>
<tr>
<td>15d</td>
<td>14 ± 4%</td>
<td>-5 ± 4% (Kd = 0.10 ± 0.005 nM)</td>
<td>4 ± 3%</td>
<td></td>
</tr>
<tr>
<td>15e</td>
<td>17 ± 2%</td>
<td>-5 ± 3% (Kd = 0.10 ± 0.05 nM)</td>
<td>13 ± 5%</td>
<td>6 ± 3%</td>
</tr>
<tr>
<td>15f</td>
<td>15 ± 1%</td>
<td>2 ± 1%</td>
<td>3 ± 1%</td>
<td></td>
</tr>
<tr>
<td>15g</td>
<td>7 ± 1%</td>
<td>7 ± 4%</td>
<td>42 ± 3% (EC50: 230 ± 37 nM)</td>
<td></td>
</tr>
<tr>
<td>15h</td>
<td>2 ± 1%</td>
<td>15 ± 4%</td>
<td>31 ± 2% (EC50: 160 ± 70 nM)</td>
<td></td>
</tr>
<tr>
<td>15i</td>
<td>10 ± 1</td>
<td>28 ± 6</td>
<td>2 ± 1</td>
<td></td>
</tr>
<tr>
<td>15j</td>
<td>31 ± 4</td>
<td>26 ± 2</td>
<td>15 ± 1</td>
<td></td>
</tr>
<tr>
<td>15k</td>
<td>61 ± 2%</td>
<td>10 ± 2%</td>
<td>16 ± 3%</td>
<td></td>
</tr>
<tr>
<td>15l</td>
<td>10 ± 4%</td>
<td>20 ± 2%</td>
<td>6 ± 3%</td>
<td></td>
</tr>
<tr>
<td>15m</td>
<td>1 ± 1%</td>
<td>2 ± 4%</td>
<td>29 ± 3% (EC50: 230 ± 70 nM)</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>33 ± 7%</td>
<td>97 ± 5%</td>
<td>10 ± 4%</td>
<td></td>
</tr>
</tbody>
</table>

"Percent maximal stimulation (% stim) at a single high concentration (10 μM) with respect to the standard agonists DAMGO (MOPr) and U69,593 (KOPr) and nociceptin (NOPr); values are an average ± SEM from three separate experiments. In brackets for selected compounds, agonist EC50/nM or antagonist Kd/nM (the antagonist dissociation constant determined against the standard agonists listed above) are given.

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Table 2. Binding Affinities ($K_i$/nM) of the New C7β-Methyl Orvinol Analogues to Opioid and NOP Receptors

<table>
<thead>
<tr>
<th></th>
<th>MOPr</th>
<th>KOPr</th>
<th>NOPr</th>
<th>DOPr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.13 ± 0.02</td>
<td>0.089 ± 0.02</td>
<td>212 ± 7</td>
<td>0.48 ± 0.26</td>
</tr>
<tr>
<td>1b</td>
<td>0.17 ± 0.05</td>
<td>0.044 ± 0.015</td>
<td>43.2 ± 13.4</td>
<td>NT</td>
</tr>
<tr>
<td>8a</td>
<td>0.08 ± 0.02</td>
<td>0.08 ± 0.03</td>
<td>97 ± 12</td>
<td>0.48 ± 0.05</td>
</tr>
<tr>
<td>8b</td>
<td>NT</td>
<td>NT</td>
<td>1270 ± 170</td>
<td>NT</td>
</tr>
<tr>
<td>8c</td>
<td>0.17 ± 0.11</td>
<td>0.04 ± 0.01</td>
<td>79 ± 8</td>
<td>0.40 ± 0.16</td>
</tr>
<tr>
<td>8e</td>
<td>0.16 ± 0.12</td>
<td>0.05 ± 0.01</td>
<td>34 ± 6</td>
<td>NT</td>
</tr>
<tr>
<td>15a</td>
<td>0.10 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>80 ± 10</td>
<td>0.25 ± 0.18</td>
</tr>
<tr>
<td>15b</td>
<td>0.20 ± 0.07</td>
<td>0.12 ± 0.03</td>
<td>820 ± 60</td>
<td>NT</td>
</tr>
<tr>
<td>15c</td>
<td>0.098 ± 0.022</td>
<td>0.11 ± 0.04</td>
<td>240 ± 50</td>
<td>NT</td>
</tr>
<tr>
<td>15d</td>
<td>0.14 ± 0.06</td>
<td>0.16 ± 0.05</td>
<td>56 ± 5</td>
<td>NT</td>
</tr>
<tr>
<td>15e</td>
<td>0.071 ± 0.014</td>
<td>0.10 ± 0.03</td>
<td>56 ± 3</td>
<td>0.47 ± 0.38</td>
</tr>
<tr>
<td>15f</td>
<td>NT</td>
<td>NT</td>
<td>26 ± 6</td>
<td>NT</td>
</tr>
<tr>
<td>15g</td>
<td>0.052 ± 0.007</td>
<td>0.094 ± 0.04</td>
<td>47.8 ± 17</td>
<td>NT</td>
</tr>
<tr>
<td>15h</td>
<td>0.09 ± 0.03</td>
<td>0.13 ± 0.05</td>
<td>62.2 ± 31</td>
<td>NT</td>
</tr>
<tr>
<td>15k</td>
<td>NT</td>
<td>NT</td>
<td>44 ± 11</td>
<td>NT</td>
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<tr>
<td>15l</td>
<td>NT</td>
<td>NT</td>
<td>571 ± 77</td>
<td>NT</td>
</tr>
<tr>
<td>15m</td>
<td>0.11 ± 0.011</td>
<td>0.14 ± 0.10</td>
<td>1455 ± 469</td>
<td>NT</td>
</tr>
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</table>

$K_i$ (nM) versus [3H]diprenorphine (for MOPr, KOPr, and DOPr); values are an average ± SEM from three separate experiments. NT: not tested.

240°C analyzer. Column chromatography was performed using RediSep prepacolumns with a Teledyne Isco CombiFlash instrument. Most ligands were tested as their hydrochloride salts, prepared by adding 5 equiv of HCl (1 N solution in diethyl ether) to a solution of compound in anhydrous methanol. Alternatively, the oxalate salt was formed by adding 1 equiv of oxalic acid in EtOH to the ligand in EtOH. All reactions were carried out under an inert atmosphere of nitrogen unless otherwise indicated. All compounds were >95% pure, as determined by microanalysis. A representative synthesis is reported here.

Arylmagnesium Halide Addition (General Procedure A). To a solution of aldehyde 4b or 11 in dry THF (10 mL/mmol of aldehyde) were added 3 equiv of Bu3NF followed by 2 equiv of arylmagnesium halide as solution in THF. The solution was then heated at reflux for 48 h, cooled to RT, and quenched with 0.05 mL of water. The mixture was allowed to stir for 5 min and then filtered over Celite. The solids were washed with hot THF, and the solution was removed of its solvent by rotary evaporation. The remaining residue was partitioned between EtOAc (20 mL) and water (10 mL). The aqueous layer was extracted twice with 5 mL of EtOAc. The pooled organic solvent was washed twice with water (5 mL) and once with brine, dried over MgSO4, and evaporated under reduced pressure. The residue was dissolved in a minimum amount of Et2O to induce crystallization. The crystals were collected by filtration and dried under vacuum.

Swern Oxidation/LiAlH4 Reduction of Secondary Alcohols (General Procedure B). A solution of oxalyl chloride (1.25 equiv) in CH2Cl2 (3 mL/mmol) was cooled to −78 °C in a one-necked flask. Into this flask was added dropwise a solution of dry DMSO (2.6 equiv) in CH2Cl2 (3 mL/mmol). The solution stirred for 5 min, and then a solution of thevinol 5 or 12 in CH2Cl2 (2 mL/mmol) was added. The mixture stirred for 20 min, and then Et3N (5 equiv) was added. The reaction was removed from the cold bath and stirred for 1 h, and water was added. The mixture was shaken, and the organic layer was separated and washed with a saturated solution of NH4Cl and then with a concentrated solution of NaHCO3. The solution was washed once more with brine, dried over magnesium sulfate, and filtered, and the solvents were removed under reduced pressure to yield crude 6 or 13 as a clear solid.

This residue was dissolved in dry THF (10 mL/mmol) and added to a stirring suspension of LiBH4 (4 equiv) in dry THF (5 mL/mmol) at 0 °C. The suspension was allowed to warm to RT and was stirred for 24 h. The reaction was cooled to 0 °C and quenched with water in THF. The mixture was filtered, rinsing the solids with hot THF. The solution was subjected to rotary evaporation to yield an oil that was subjected to silica gel column chromatography, eluting with 15% EtOAc in petroleum ether to yield two constituents, 7 or 14 (as the major product), as a high Rf component, and 9 or 16 (as the minor product), with lower Rf.

O-Demethylation Using NaSPr/HMPA (General Procedure C). A solution of thevinol 7, 9, 14, or 16 in dry HMPA (6 mL/mmol) was added sodium propanethiolate (6 equiv). The reaction was stirred for 3 h at 115 °C and then cooled to RT and quenched with 7 mL/mmol of a concentrated solution of NH4Cl. The mixture was extracted three times with Et2O. The organic layer was then extracted five times with water and once with brine, dried over MgSO4, and filtered, and the solvents were removed under reduced pressure. The residue was then subjected to silica gel flash column chromatography, eluting with a gradient of EtOAc in petroleum ether. The fractions containing the compound of interest were then evaporated to dryness, dissolved in a 2 M solution of HCl in EtOH, and then induced to crystallize upon addition of EtOAc. The crystals were collected by filtration and dried under vacuum.

N-Cyclopropylcarbonyl-7a-formyl-7β-methyl-6,14-endoethenotetrahydronorthebaine (4b). To a solution of 13.61 g (37.29 mmol) N-CPCNorthebaine in 20 mL of methacrolein was added 3.49 g of LiBF4. The resulting solution was stirred for 16 h at RT. Into this solution was added 30 mL of CH2Cl2, and the mixture was extracted with water (10 mL × 3) and brine (5 mL). The solution was dried, filtered, and removed of solvent on a rotary evaporator to afford a dark red syrup. This material was subjected to silica gel flash column chromatography, eluting with 10% EtOAc in petroleum ether to afford 5.91 g of the faster running component 9 (as the major product) and 16 (as the minor product) as a white solid. 1H NMR (400 MHz, CDCl3) δ 9.85 (s, 1H), 6.67 (d, 1H, J = 8.0 Hz), 6.57 (d, 1H, J = 8.0 Hz), 6.14—6.07 (2d, 3H, J = 8.0 Hz).
N-Cyclopropylcarbonyl-7α-formyl-7β-methyl-6,14-endoethanotetrahydronorthebaine (11). Aldehyde 4b (500 mg) was dissolved in 15 mL of EtOH. Into this solution was added 50 mg of Na2CO3 and 3.4 mL of ZnCl2. The mixture was stirred for 2 h. The mixture was filtered, and the solvents were removed under reduced pressure to yield 510 mg of 51. 

NMR (400 MHz, CDCl3) δ 9.54 (s, 0.5H), 9.45 (s, 0.5H), 6.69 (d, 1H, J = 8.0 Hz), 6.59 (d, 1H, J = 8.0 Hz), 6.14 (t, 1H, J = 8.0 Hz), 5.77 (dd, 1H, J1 = 12.0 Hz, J2 = 0.55 Hz), 5.35 (d, 0.5H, J = 4.0 Hz), 4.93 (s, 1H), 4.80 (d, 0.5H, J = 8.0 Hz), 4.64 (dd, 1H, J1 = 8.0 Hz, J2 = 4.0 Hz), 4.15 (dd, 1H, J1 = 8.0 Hz, J2 = 4.0 Hz), 3.85 (s, 3H), 3.72 (2s, 3H), 3.49 (dt, 1H, J = 1.72 Hz), 0.26–1.72 (m, 1H), 1.35 (s, 3H), 1.08 (m, 2H), 0.82 (m, 2H). At RT, the 1H NMR spectrum of this compound in DMSO-d6 has two signals at δ 9.408 (s, 0.5H) and δ 9.375 (s, 0.5H) that coalesce when running the 13C NMR experiment at 360 K. ESIMS: m/z 436 (M + H+), 100.

ASSOCIATED CONTENT

S Supporting Information

Full characterization of final compounds; microanalysis and HPLC; pharmacological studies. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jmedchem.5b00130.

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Notes

The authors declare the following competing financial interest(s): Subsequent to the preparation of the manuscript the compounds disclosed have been licensed to a biopharmaceutical company.

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ABBREVIATIONS

MOP receptor, mu opioid receptor; DOP receptor, delta opioid receptor; KOP receptor, kappa opioid receptor; NOP receptor, nociceptin opioid peptide receptor; EKC, ethylketocyclazocine; N/OFQ, nociceptin/orphanin FQ.

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