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Use of a Robust Dehydrogenase from an Archael Hyperthermophile in Asymmetric Catalysis–Dynamic Reductive Kinetic Resolution Entry into (*S*)-Profens

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Hyperthermophilic archaea are of great interest in evolutionary microbiology, owing to their ability to withstand high temperatures, and often extremes of pressure, pH and salinity. Enzymes from these organisms[1] may offer particular opportunities for asymmetric synthesis, complementary to approaches with mesophilic enzymes,[2] or those involving enzyme[3] and pathway[4] reengineering. However, perhaps due to a bias that hyperthermophilic enzymes have "narrow substrate specificities,"[5] archaeal extremophiles remain a largely untapped resource in asymmetric synthesis.[6]

Herein, we disclose a remarkably general Dynamic Reductive Kinetic Resolution (DYRKR) entry into (*S*)-profens, including several important NSAIDs. The enzyme employed is alcohol dehydrogenase (ADH)-10, one of 13 annotated ADHs in the hyperthermophile *Sulfolobus solfataricus*. Protein phylogenetic analysis of this paralogous family indicates SsADH-10 is most closely related to homologues in distant taxa (Fig. 1). The highest identity between SsADH-10 and any other SsADHs is only 34%, suggesting that the SsADH family was established prior to the emergence of other archaeal lineages. Though not described as such, the SsADH-10 appears to be the only SsADH isozyme for which structural information is available in the pdb.[7]

The requisite, 2-arylpropionaldehydes were readily assembled via Pd(0)-catalyzed arylation of *t*-butyl propionate under Buchwald-Hartwig-type[8] conditions, followed by reduction to the aldehyde (LDBBA[9] or LAH/DMP oxid-*see* SI). Optimal DYRKR conditions (Table 1-80°C, pH 9) led to efficient throughput of *rac*-aldehyde to the (*S*)-2-arylpropionaldehyde, particularly with *m*- and *p*-substitution. Notably, (*S*)-profenols corresponding to the NSAIDs naproxen (**3b**, scaled to 1 gram @ 98% yield and 95% ee), ibuprofen (**3d**, IP), flurbiprofen (**3h**, FlP), fenoprofen (**3j**, FP) and ketoprofen (**3l**, KP) were obtained in excellent yields (up to 96%) and high enantioselectivity (up to 99 %).

Naproxen is FDA-approved as the active (*S*)-antipode. While most individuals can invert (*R*)-ibuprofen to the (*S*)-antipode, the pathway is inefficient for KP[10a] and FlP.[10b] Moreover, the recent observation that the profen-CoA thioester intermediates inhibit G6PDH,[10c] argues for "chiral switching" to single (*S*)-antipodes.[10d] Entries into (*S*)-profens[11,12] include asymmetric

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Supporting Information Available: Details of SsADH-10 expression, synthesis, spectra, DYRKR and modeling. This material is available free of charge via the Internet at http://pubs.acs.org.

hydrogenation (NP 98% ee, IP 97% ee),[11g] and hydroformylation (IP, 92% ee).[11f] DKR processes include enantioselective crystallization (NP >99% ee),[11b] DYRKR with H_2 as reductant under Ru(II) catalysis (IP 92% ee),[11d] and lipase/Ru(II)-mediated-DKR of allylic acetates, followed by Cu-mediated Grignard-arylation (FlP 97% ee;[11c] Knochel arylation:[11e] IP 97% ee). The hydrovinylation/oxidation approach is impressive (IP, FP, FlP, NP >96% ee),[11a] but access to KP requires late stage arylation. Thus, the broad side chain tolerance of SsADH-10 makes the method presented here among the most generally (*S*)-selective.

To explore how these extended hydrophobic substrates bind to SsADH-10, docking was carried out (Fig. 2) for the (*S*)-antipodes of flurbiprofenal, naproxenal, ketoprofenal and fenoprofenal. A detailed discussion of the approach and results is provided in the SI. Briefly, W95 is seen as enforcing (*S*)-selectivity, with ligands clustering into two distinct distal ring binding modes. "Channel-gating"-L272 and L295 appear to form a hydrophobic pocket for naproxenal and flurbiprofenal. For the more flexible ketoprofenal and fenoprofenal, edge-to-face interactions with W117 and F49 are proposed.

From a practical viewpoint, we have also found that SsADH-10 may be engaged in a "thermal recycling" approach that may be generalizable to other hyperthermophilic enzymes. Namely, while 30 vol% cosolvent is often needed to dissolve hydrophobic DH substrates,[13] we use a higher T (80°C) @ just 5% EtOH (solvent and biorenewable reductant). Importantly, upon completion of the reaction, cooling to rt allows the product to precipitate and be collected by filtration (*see TOC graphic and* SI). Reclaimed SsADH may be recycled (5 cycles @ 94-96 % ee). Given the growing interest in thermophilic enzymes in synthesis,[1,14] and in engineering thermostability into mesophilic enzymes,[15] this "thermal switching" approach is likely to find broad application, well beyond the domain of geothermal dehydrogenases.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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REFERENCES

(1). Atomi H. Curr. Opin. Chem. Biol 2005;9:166–173. [PubMed: 15811801]

(2). Broussy S, Cheloha RW, Berkowitz DB. Org. Lett 2009;11:305–8. [PubMed: 19128188]

(3) (a). Reetz MT, Wu S. J. Am. Chem. Soc 2009;131:15424–15432. [PubMed: 19807086] (b) Kourist R, Hohne M, Bornscheuer UT. Chem. Unserer Zeit 2009;43:132–142. (c) Kazlauskas RJ, Bornscheuer UT. Nat. Chem. Biol 2009;5:526–529. [PubMed: 19620988] (d) Jackel C, Kast P, Hilvert D. Annu. Rev. Biophys 2008;37:153–173. [PubMed: 18573077] (e) Reetz MT, Wang L-W, Bocola M. Angew. Chem., Int. Ed 2006;45:1236–1241. (f) Qian Z, Lutz S. J. Am. Chem. Soc 2005;127:13466–13467. [PubMed: 16190688]

(4) (a). Ran N, Frost JW. J. Am. Chem. Soc 2007;129:6130–6139. [PubMed: 17451239] (b) Li W, Xie D, Frost JW. J. Am. Chem. Soc 2005;127:2874–2882. [PubMed: 15740122] (c) Moradian A, Benner SA. J. Am. Chem. Soc 1992;114:6980–7.

(5). Radianingtyas H, Wright PC. FEMS Microbiol. Rev 2003;27:593–616. [PubMed: 14638414]

(6) (a). Moore JC, Pollard DJ, Kosjek B, Devine PN. Acc. Chem. Res 2007;40:1412–1419. [PubMed: 18052114] (b) Anderson BA, Hansen MM, Harkness AR, Henry CL, Vicenzi JT, Zmijewski MJ. J. Am. Chem. Soc 1995;117:12358–12359.

(7) (a). For elegant biophysical studies, see: Esposito L, Bruno I, Sica F, Carlo A. Raia, Giordano A, Rossi M, Mazzarella L, Zagari A. Biochemistry 2003;42:14397–14407. [PubMed: 14661950] ; (b) Esposito L, Sica F, Raia CA, Giordano A, Rossi M, Mazzarella L, Zagari A. J. Mol. Biol 2002;318:463–477. [PubMed: 12051852]

(8) (a). Moradi WA, Buchwald SL. J. Am. Chem. Soc 2001;123:7996–8002. [PubMed: 11506555] (b) Jorgensen M, Lee S, Liu X, Wolkowski JP, Hartwig JF. J. Am. Chem. Soc 2002;124:12557–12565. [PubMed: 12381200]

(9). Kim MS, Choi YM, An DK. Tetrahedron Lett 2007;48:5061–5064.

(10) (a). Jamali F, Brocks DR. Clin. Pharmacokin 1990;19:197–217. (b) Geisslinger G, Loetsch J, Menzel S, Kobal G, Brune K. Br. J. Clin. Pharmacol 1994;37:392–394. [PubMed: 8018462] (c) Asensio C, Levoin N, Guillaume C, Guerquin M-J, Rouguieg K, Chretien F, Chapleur Y, Netter P, Minn A, Lapicque F. Biochem. Pharm 2007;73:405–416. [PubMed: 17094951] (d) Agranat I, Caner H, Caldwell J. Nature: Rev. Drug Disc 2002;1:753–768.

(11) (a). Smith CR, RajanBabu TV. J. Org. Chem 2009;74:3066–3072. [PubMed: 19317393] (b) Noorduin WL, Kaptein B, Meekes H, van Enckevort WJP, Kellogg RM, Vlieg E. Angew. Chem., Int. Ed 2009;48:4581–4583. (c) Norinder J, Bogar K, Kanupp L, Baeckvall J-E. Org. Lett 2007;9:5095–5098. [PubMed: 17956114] (d) Li X, List B. Chem. Commun 2007:1739–1741. (e) Harrington-Frost N, Leuser H, Calaza MI, Kneisel FF, Knochel P. Org. Lett 2003;5:2111–2114. [PubMed: 12790541] (f) Nozaki K, Sakai N, Nanno T, Higashijima T, Mano S, Horiuchi T, Takaya H. J. Am. Chem. Soc 1997;119:4413–4423. (g) Uemura T, Zhang X, Matsumura K, Sayo N, Kumobayashi H, Ohta T, Nozaki K, Takaya H. J. Org. Chem 1996;61:5510–5516.

(12). During these studies, one example (mesophilic HLADH, ibuprofenal) of a related DYRKR was reported: Giacomini D, Galletti P, Quintavalla A, Gucciardo G, Paradisi F. Chem. Commun 2007:4038–4040.

(13). Musa MM, Ziegelmann-Fjeld KI, Vieille C, Zeikus JG, Phillips RS. J. Org. Chem 2007;72:30–34. [PubMed: 17194078]

(14) (a). Voss CV, Gruber CC, Faber K, Knaus T, Macheroux P, Kroutil W. J. Am. Chem. Soc 2008;130:13969–13972. [PubMed: 18821754] (b) Musa MM, Ziegelmann-Field KI, Vieille C, Zeikus JG, Phillips RS. Angew. Chem., Int. Ed 2007;46:3091–3094. (c) van den Burg B. Curr. Opin. Microbiol 2003;6:213–218. [PubMed: 12831896]

(15) (a). Shaw BF, Schneider GF, Bilgicer B, Kaufman GK, Neveu JM, Lane WS, Whitelegge JP, Whitesides GM. Protein Sci 2008;17:1446–1455. [PubMed: 18451358] (b) Reetz MT, Carballeira JD, Vogel A. Angew. Chem., Int. Ed 2006;45:7745–7751.

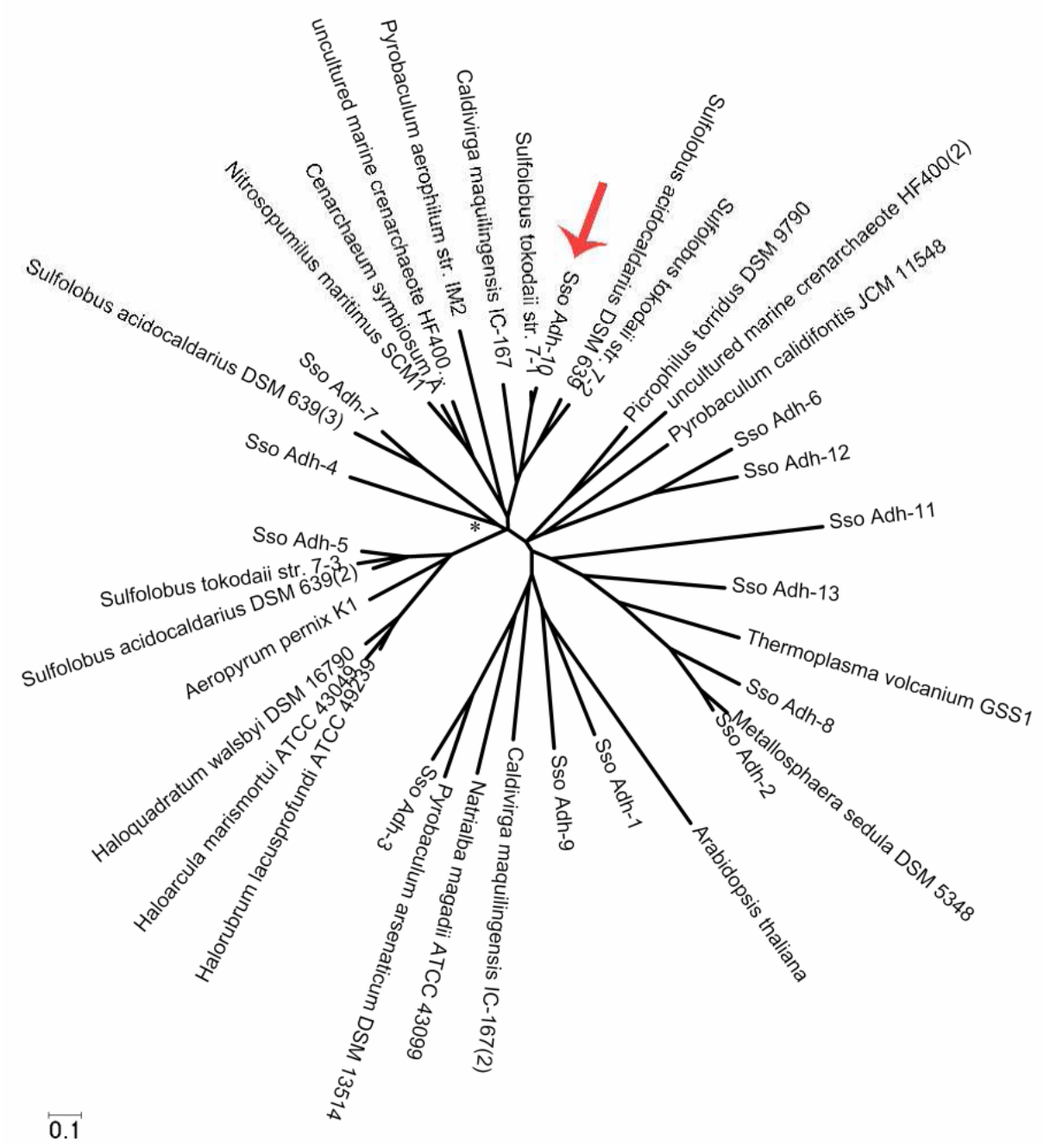


Figure 1.

Protein phylogeny of the SsADH proteins. A consensus neighbor joining distance tree is shown of all SsADHs and homologues of highest sequence identity in related taxa. Distances are indicated by the bar (lower left corner) and represent 10 substitutions per 100 residues. Percent occurrence among 100 trees was greater than 50% for all nodes except those indicated with an asterisk.

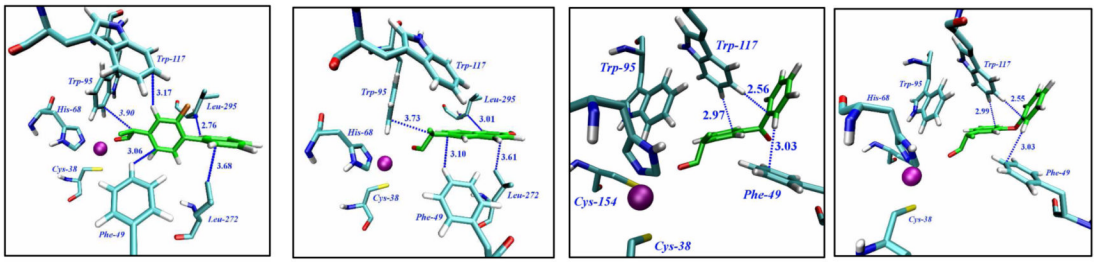
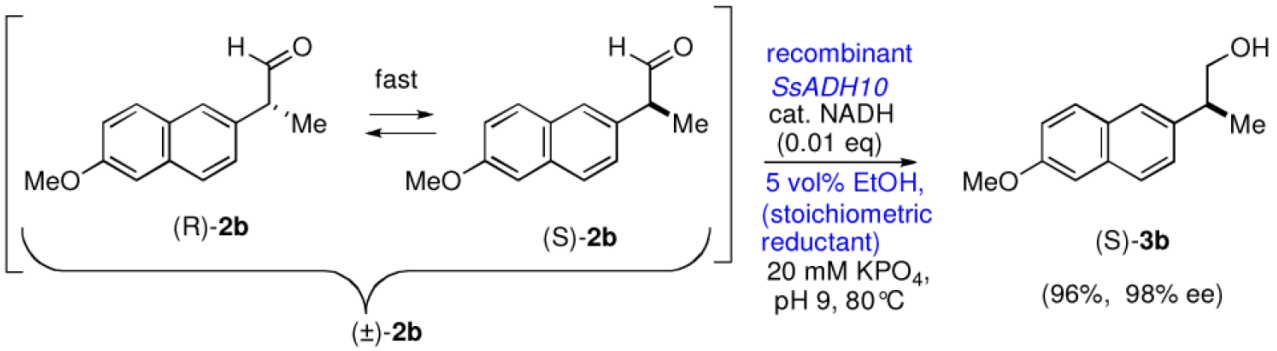


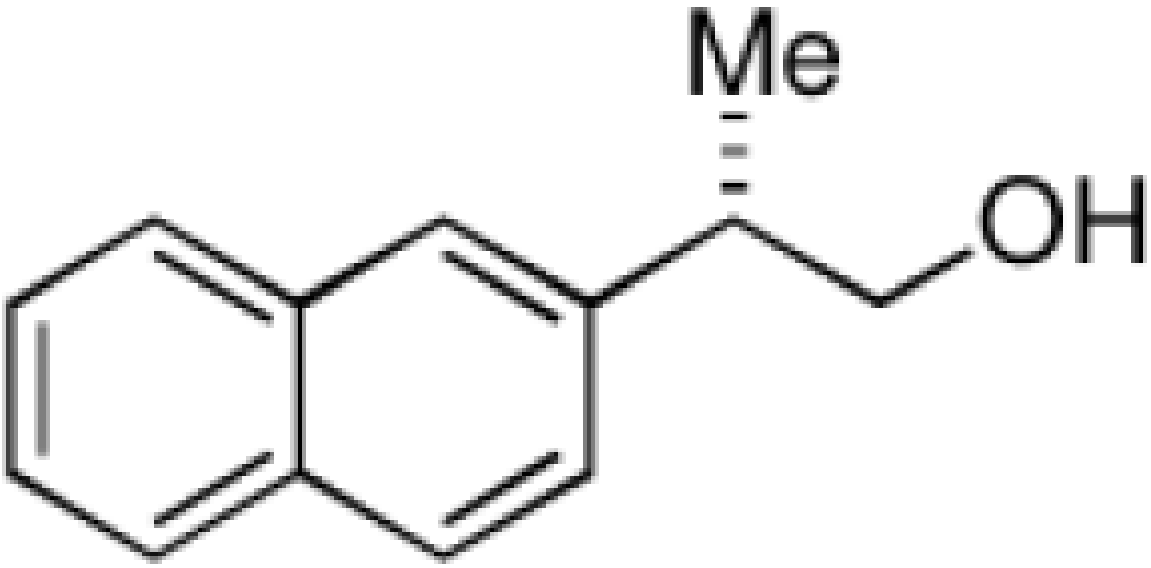
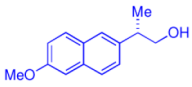
Figure 2.

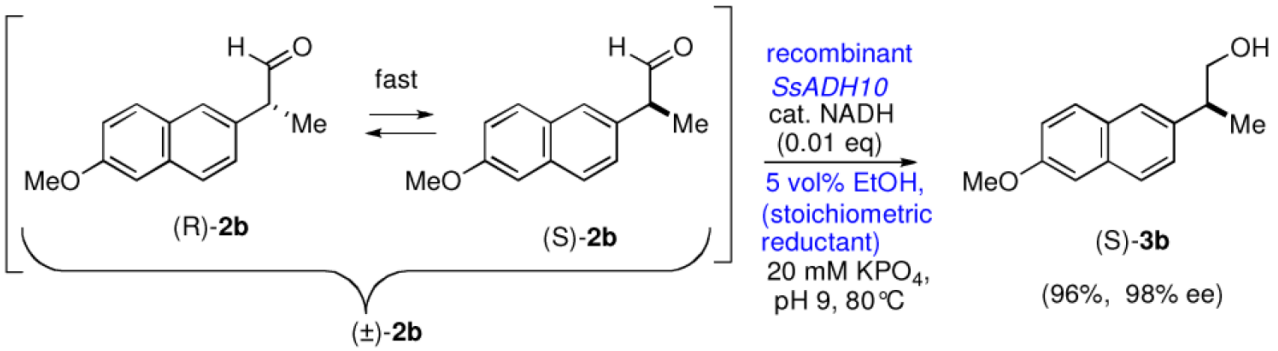
Structures of thermally relaxed (GROMACS 4.07) SsADH-10 (from 1R37) to which has been docked (Autodock Vina - left to right-): (i) (*S*)-flurbiprofenal (ii) (*S*)-naproxenal (iii) (*S*)-ketoprofenal and (iv) (*S*)-fenoprofenal (Zn ligation sphere: H68, C38, C154 and substrate carbonyl)

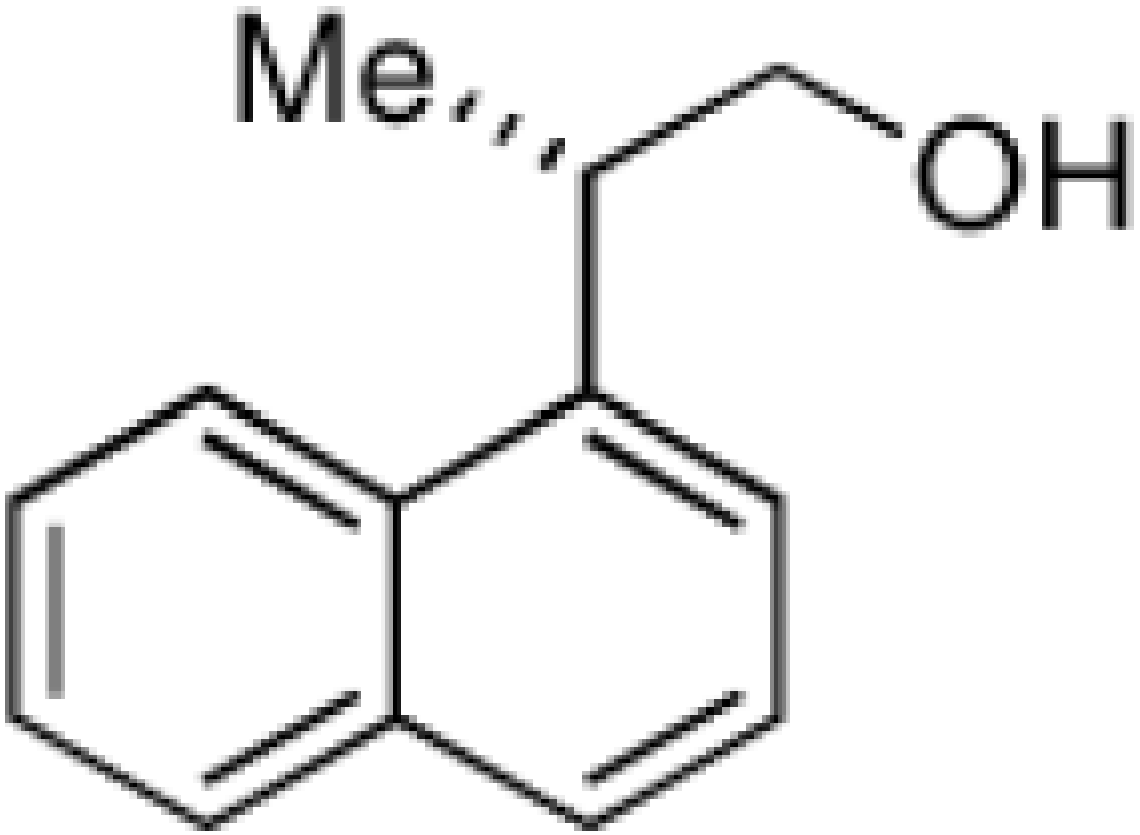
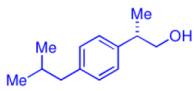
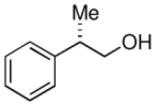
Table 1

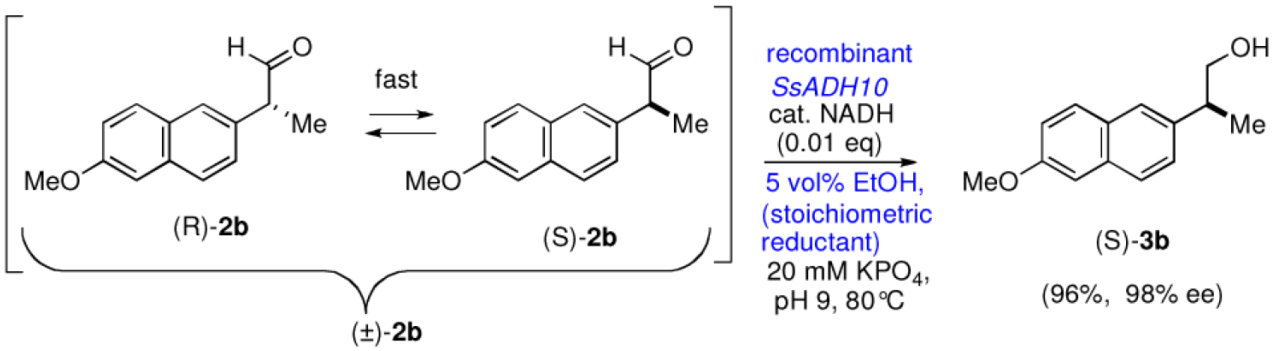
SsADH10-Mediated DYRKR Entry into Profenols

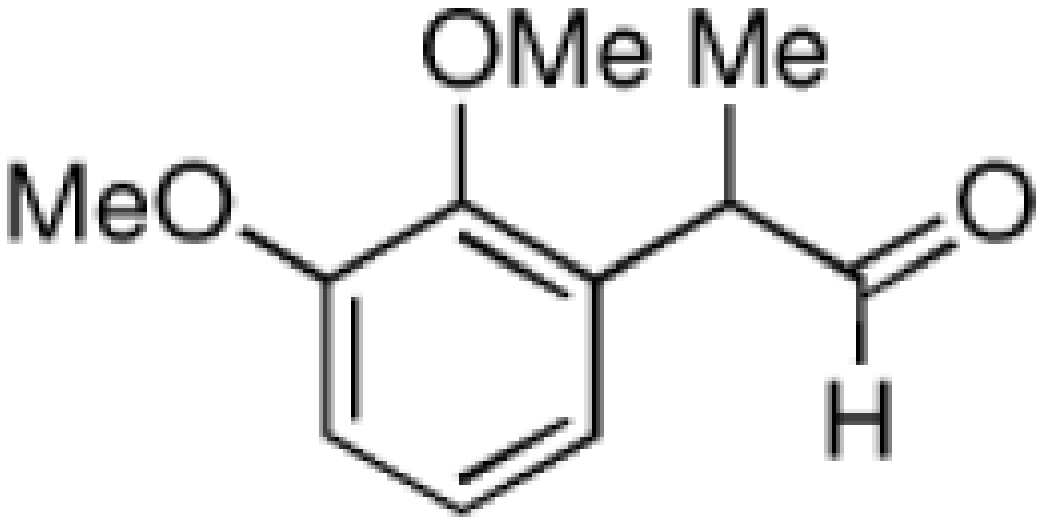


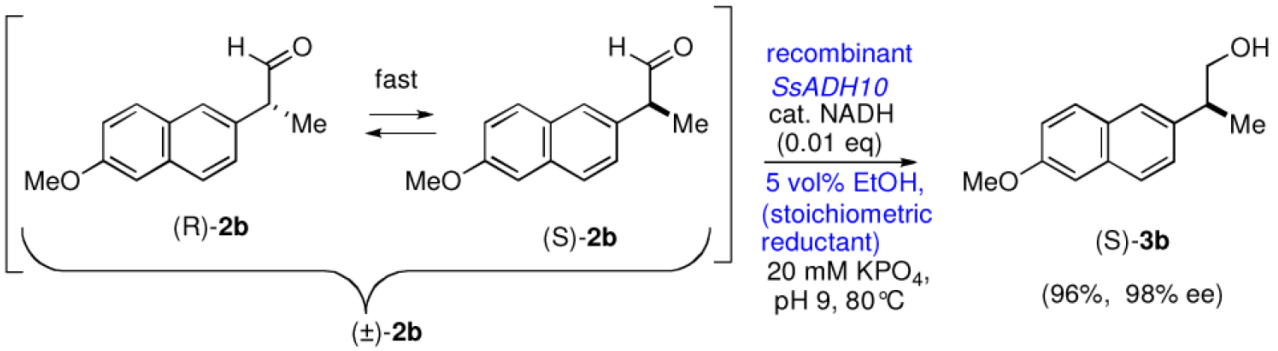
Cpd No.	DYRKR Product[a]	t(h)	Yield (%)[b]
3a		18	57%
3b		18	96%



Cpd No.	DYRKR Product[a]	t(h)	Yield (%)[b]
3c		18	90%
3d		18	92%
3e		18	74%



Cpd No.	DYRKR Product[a]	t(h)	Yield (%)[b]
2f	 (redn not obsd)	18	recvd Sl



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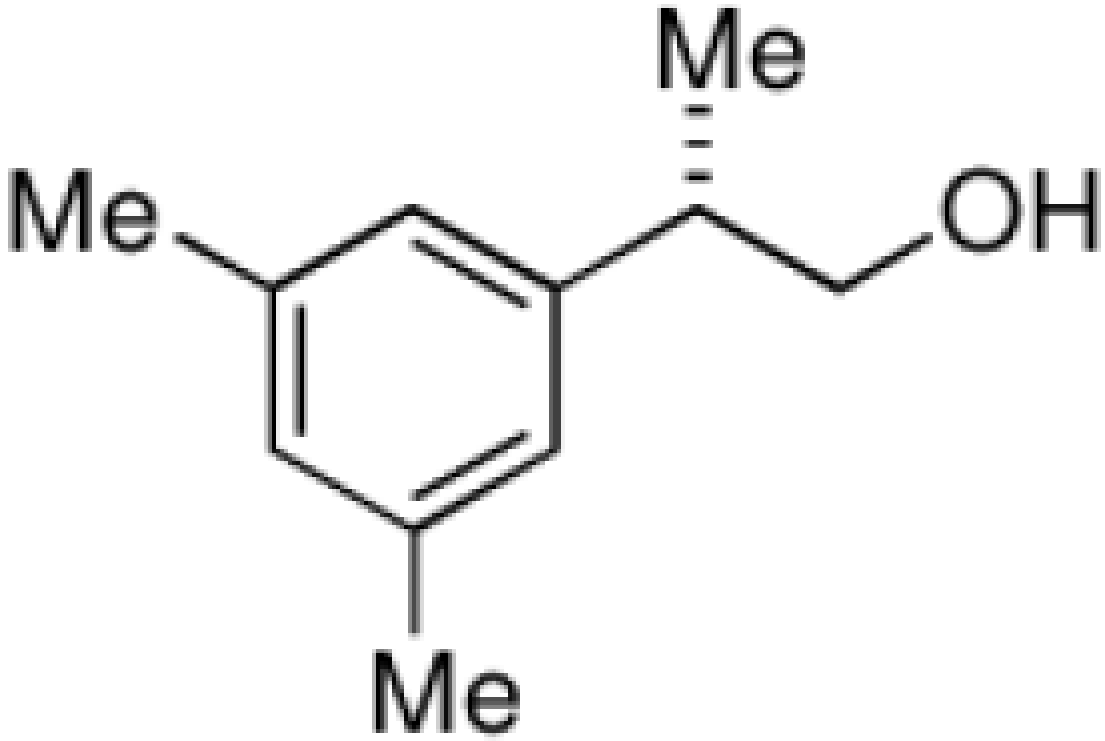
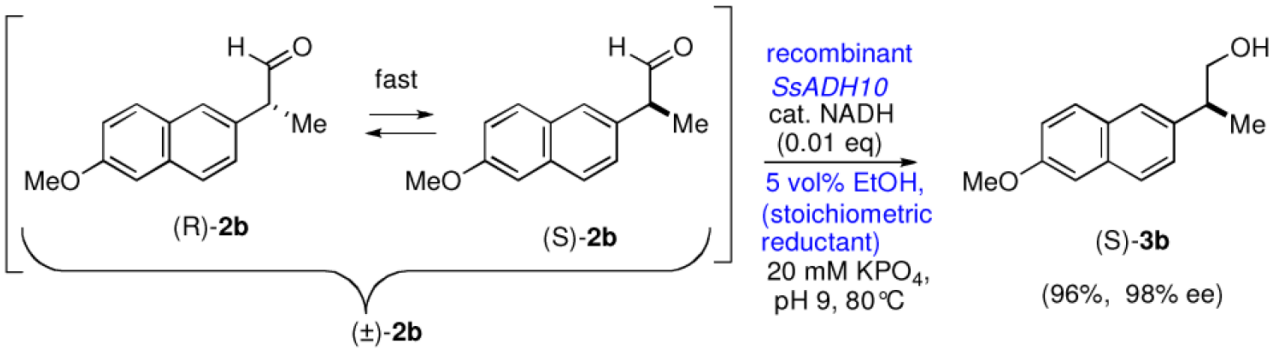
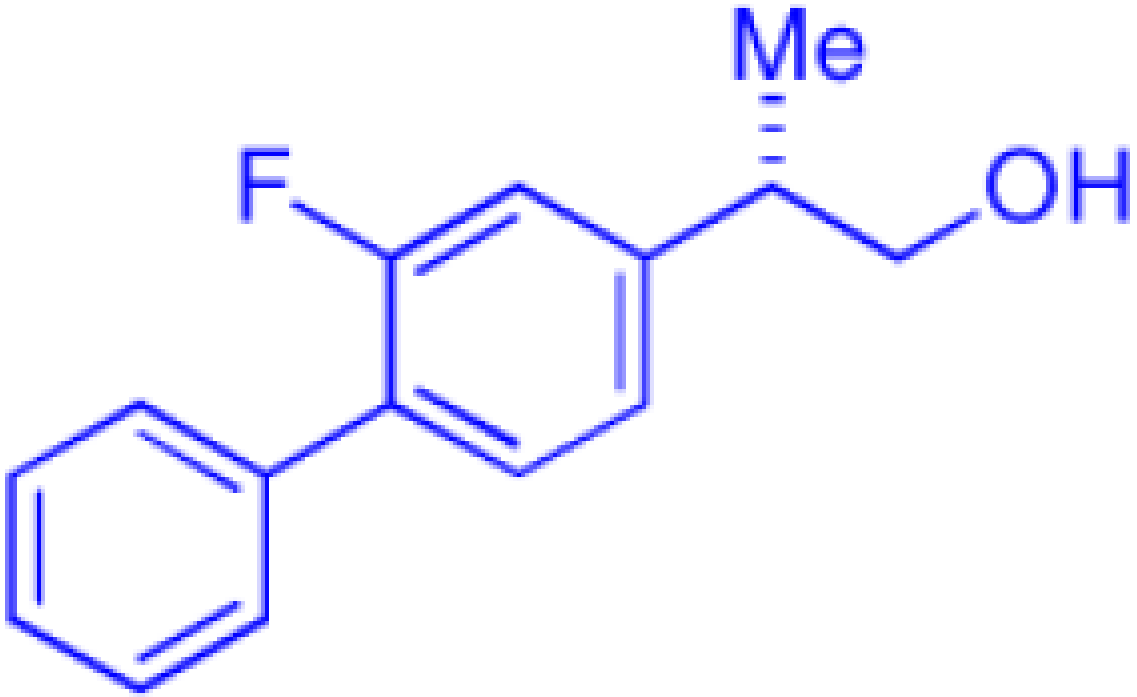
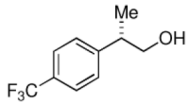
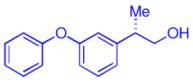
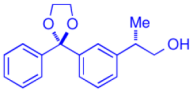
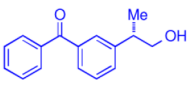
3g		18	99%



Cpd No.	DYRKR Product[a]	t(h)	Yield (%)[b]
3h		18	77%
3i		24	55%
3j		12	85%
3k		18	95%
3l		18	85%

[a] DYRKR performed on a 1 mmol scale (1 mol% NADH; 5 vol% EtOH)

[b] Isolated yields

[c] ee's by chiral LC or GC. Blue - profen drug precursor.