

Cite this: *Chem. Commun.*, 2011, **47**, 7332–7334

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## Chiral inversion of 2-arylpropionyl-CoA esters by human $\alpha$ -methylacyl-CoA racemase 1A (P504S)—a potential mechanism for the anti-cancer effects of ibuprofen†

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Received 9th February 2011, Accepted 26th April 2011

DOI: 10.1039/c1cc10763a

**Metabolic chiral inversion of 2-arylpropanoic acids (2-APAs; † ‘profens’), such as ibuprofen, is important for pharmacological activity. Several 2-APA-CoA esters were good racemisation substrates for human AMACR 1A, suggesting a common chiral inversion pathway for all 2-APAs and an additional mechanism for their anti-cancer properties.**

Non-steroidal anti-inflammatory drugs (NSAIDs) are widely used in human and veterinary medicine for their analgesic and anti-inflammatory properties.<sup>1</sup> They inhibit cyclo-oxygenase-1 and -2 (COX-1 and -2), reducing production of prostaglandins and other inflammatory mediators. COX-1 is present in all tissues, while COX-2 levels are normally low but increase in response to tissue injury.<sup>1</sup> Common examples include aspirin, indomethacin, diclofenac and the 2-arylpropanoic acids (2-APAs; a.k.a. profens), including ibuprofen **1**. 2-APA drugs contain a chiral centre and their *S*-enantiomers potently inhibit COX activity, while the *R*-enantiomers are much less active.<sup>2,3</sup> These drugs are often given as racemic mixtures. Ibuprofen **1**,<sup>4–7</sup> fenoprofen **3**,<sup>3,8</sup> flobufen,<sup>9</sup> flurbiprofen **4**,<sup>10</sup> ketoprofen **5**<sup>2</sup> and naproxen **6**<sup>11</sup> undergo uni-directional conversion to the single *S*-enantiomer *in vivo*. *R*-Ibuprofen **1** is converted to *R*-ibuprofenoyl-CoA **2**<sup>12,13</sup> and chirally inverted by an epimerase.<sup>7,14,15</sup> Finally, hydrolysis of the CoA ester gives *S*-ibuprofen **1**. Other 2-APAs are assumed to be inverted by the same enzymes as for ibuprofen **1**, but this has not been proven.

Cloning of ‘ibuprofenoyl-CoA epimerase’ showed that it was identical to  $\alpha$ -methylacyl-CoA racemase (AMACR), which also catalyses chiral inversion of other 2-methyl-fatty acyl-CoA esters.<sup>16</sup> The reaction involves removal of the substrate  $\alpha$ -proton followed by non-stereoselective reprotonation.<sup>17</sup> Protein levels and activity are increased in prostate, some colon and other cancers,<sup>16</sup> and AMACR has attracted interest as a novel marker<sup>18</sup> and drug target.<sup>19,20</sup>

Although the acyl groups of AMACR substrates are known to be structurally diverse,<sup>16</sup> no systematic study of substrate structure has been reported. This communication reports the first such systematic study and shows that all of the tested 2-APA-CoA esters are good substrates. High doses of ibuprofen reduce the risk of developing prostate cancer<sup>26</sup> and these results suggest that the interaction of 2-APA-CoA esters with AMACR may contribute to this chemopreventive effect.

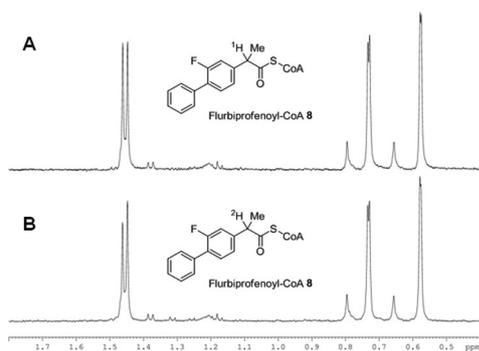
Initially, a number of 2-APA-CoA esters were synthesized for evaluation. Ibuprofenoyl-CoA **2** was chosen, as a known substrate for native rat AMACR<sup>14</sup> and the homologous MCR from *M. tuberculosis*.<sup>21</sup>  $\pm$ -Fenoprofenoyl-CoA **7**,  $\pm$ -flurbiprofenoyl-CoA **8**, and *S*-ketoprofenoyl-CoA **9** were synthesized, as these 2-APAs undergo chiral inversion *in vivo*.<sup>2,3,8,10</sup> *S*-Naproxenoyl-CoA **10** was also synthesized, as it is structurally related but its chiral inversion *in vivo* is reported to be extremely limited.<sup>11</sup> The 2-APAs reacted with carbonyl diimidazole<sup>20,22</sup> to form the acyl-imidazole intermediates, the presence of which was confirmed by <sup>1</sup>H NMR. These intermediates were immediately treated with CoA-SH, to afford the desired esters on ~10 mg scales (ESI, † Scheme S1). *S*-2-Methyldecanoyl-CoA **11** was also synthesized as a known substrate of human recombinant AMACR 1A.<sup>17,23</sup>

These acyl-CoA esters were incubated at *ca.* 400  $\mu$ M with human AMACR 1A in the presence of <sup>2</sup>H<sub>2</sub>O for >16 h and activity was monitored by exchange of the  $\alpha$ -proton for <sup>2</sup>H by <sup>1</sup>H NMR.<sup>17</sup> Exchange of the  $\alpha$ -proton for <sup>2</sup>H at *ca.* 70–90% conversion was observed for all 2-APA-CoAs. The signal for the methyl group on C-2 appears as an asymmetrical doublet (Fig. 1), composed of the unresolved triplet of the <sup>2</sup>H-labelled product superimposed on the doublet of unreacted substrate. There was also a reduction in the intensity of the signal for 2-H. The known substrate, *S*-2-methyldecanoyl-CoA **11**, was converted >95% under the same conditions.<sup>17</sup> No exchange was observed in negative controls containing heat-inactivated enzyme.

Experiments were then performed to determine whether chiral inversion of the 2-APA-CoA had also occurred in addition to  $\alpha$ -proton exchange. Thus, *ca.* 10 mg of *S*-ketoprofenoyl-CoA **9** and *S*-naproxenoyl-CoA **10** were separately incubated with AMACR in <sup>1</sup>H<sub>2</sub>O-containing buffer. The product CoA esters were hydrolysed and the 2-APAs were converted to the

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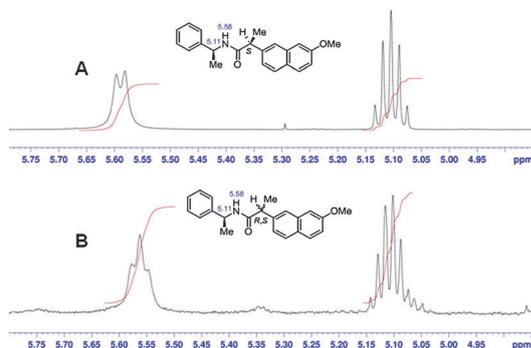
† Electronic supplementary information (ESI) available: Synthetic methods; kinetic plots. See DOI: 10.1039/c1cc10763a



**Fig. 1**  $^2\text{H}$ -Exchange of  $\pm$ -flurbiprofenoyl-CoA **8** by AMACR 1A, showing change in methyl group splitting at  $\delta$  1.45 p.p.m. (A) Heat-inactivated enzyme; (B) Active enzyme.

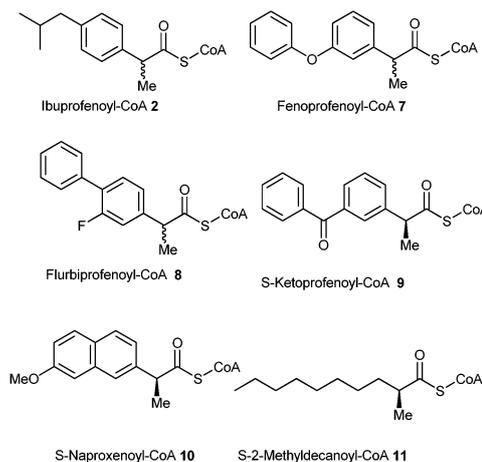
diastereomeric *N*-(*S*-1-phenylethyl)amides **12** and **13**. The  $^1\text{H}$  NMR spectra showed two overlapping series of peaks corresponding to the 2-H, the 2-Me, the NCHMe and the amide NH (Fig. 2B), showing that chiral inversion had occurred. The ratio of the two epimeric products in both cases was close to 1 : 1, consistent with observations for 2-methyldecanoyl-CoA **11** ( $K_{\text{eq}} = 1.09 \pm 0.14$ ; *S/R*).<sup>17</sup> Similar treatment of the 2-APAs without exposure to the enzyme gave single sets of signals, confirming that the configuration of the chiral centre was maintained during derivatization (Fig. 2A). Exchange of the  $\alpha$ -proton is obligatory for chiral inversion and, since no exchange is observed with heat-inactivated enzyme, this demonstrates that chiral inversion is enzyme-catalysed.

Kinetic parameters for the 2-APA-CoA and *S*-2-methyldecanoyl-CoA esters were then determined (Table 1). All the 2-APA-CoA esters were good substrates of human AMACR 1A. Flurbiprofenoyl-CoA **8**, ibuprofenoyl-CoA **2** and naproxenoyl-CoA **10** were converted about as efficiently as *S*-2-methyldecanoyl-CoA **11** (as judged by  $k_{\text{cat}}/K_{\text{m}}$ ). The results also suggest that the limited chiral inversion of flurbiprofen<sup>10</sup> in humans is due to low conversion to its CoA ester **8** *in vivo* rather than it not being a chiral inversion substrate. Ketoprofenoyl-CoA **9** was converted *ca.* twice as efficiently as *S*-2-methyldecanoyl-CoA **11**. Fenoprofenoyl-CoA **7** was by far the best substrate ( $k_{\text{cat}}/K_{\text{m}} = ca. 1400 \text{ M}^{-1} \text{ s}^{-1}$ ), largely



**Fig. 2** Chiral inversion of naproxenoyl-CoA **10** by AMACR 1A. The spectra show the signals for the  $\alpha$ -proton of 1-phenylethylamine and the NH of the amide linkage. (A) Without exposure to enzyme; (B) Following exposure to AMACR 1A. The signals appear as two superimposed doublets at 5.55 p.p.m. and two superimposed quintets at 5.10 p.p.m.

**Table 1** Substrate kinetic parameters for AMACR 1A. The parameters shown are derived using the Direct Linear Plot<sup>24,25</sup>



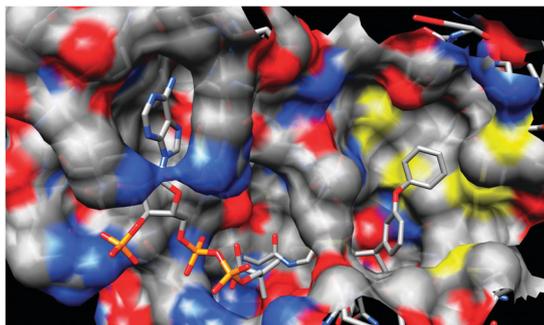
Substrate	$K_{\text{m}}$ ( $\mu\text{M}$ )	$V_{\text{max}}$ ( $\text{nmol min}^{-1} \text{mg}^{-1}$ )	$k_{\text{cat}}$ ( $\text{s}^{-1}$ )	$k_{\text{cat}}/K_{\text{m}}$ ( $\text{M}^{-1} \text{s}^{-1}$ )
<b>2</b>	74	9.36	0.0073	99
<b>7</b>	2.3	4.16	0.0033	1426
<b>8</b>	26	5.12	0.0040	156
<b>9</b>	52	19.2	0.0150	290
<b>10</b>	68	12.2	0.0095	140
<b>11</b>	277	39.3	0.0310	112

due to the very low estimated  $K_{\text{m}}$  value (2.3  $\mu\text{M}$  *cf.* 26–74  $\mu\text{M}$  for other substrates). Examination of the kinetic plots for **7** showed near-saturation even at the lowest substrate concentrations and it is possible that the  $K_{\text{m}}$  value is significantly lower than estimated by this assay. It was not possible to use significantly lower substrate concentrations, as a tight binding situation would occur, *i.e.* the concentrations of substrate and enzyme would be similar. Interestingly, the  $K_{\text{m}}$  for **7** is of similar magnitude to the  $K_{\text{i}}$  values for the best inhibitors of the rat enzyme (*ca.* 0.9  $\mu\text{M}$ ).<sup>20</sup>

Literature inhibitors of AMACR<sup>20</sup> increase the acidity of the  $\alpha$ -proton using electron-withdrawing groups, to facilitate deprotonation and mimic the deprotonated intermediate. The aliphatic side-chain of *S*-2-methyldecanoyl-CoA **11** is electron-donating and replacement with any aryl side-chain will make the  $\alpha$ -proton more acidic. 2-APA-CoA substrates are expected to be more tightly bound based on this argument and lower  $K_{\text{m}}$  values are observed. Substrates with aromatic rings substituted with electron-withdrawing groups (*e.g.* **8**) are expected to have particularly acidic  $\alpha$ -protons and this may explain its tight binding.

There is no reported structure for AMACR, but the structure of the *M. tuberculosis* homologue with a number of acyl-CoA has been reported.<sup>21</sup> These structures show the CoA moiety locked into the active site by a network of hydrogen bonds and ionic interactions. The carboxylate thioester and methyl groups of the substrate are close to the catalytic residues. The substrate side-chains are directed to the methionine-rich surface at the active site entrance. AMACR is expected to bind substrates in broadly similar manner and this explains the diverse structures of known substrates.<sup>16</sup> However, these factors do not explain the low  $K_{\text{m}}$  value of fenoprofenoyl-CoA **7**.

*Post facto* molecular modelling studies were undertaken to try to rationalize the binding of 2-APA-CoAs to AMACR.



**Fig. 3** Binding of *R*-fenoprofenoyl-CoA **7** modelled by docking into the active site of the AMACR homologue from *M. tuberculosis*.<sup>21</sup>

The structures of MCR complexed with *S*- or *R*-ibuprofenoyl-CoA **2**<sup>21</sup> were used as starting models. Binding of the CoA moiety and chiral centre are identical for all models, regardless of their stereochemical configuration, e.g. *R*-fenoprofenoyl-CoA **7** (Fig. 3). In each case, the side-chain projects towards the methionine-rich surface.<sup>21</sup> In all but one case (M198/F194), the predicted side-chain binding residues in AMACR are identical to those in MCR (ESI,† Fig. S1). Substrates with *meta*-substituted aromatic rings (e.g. **7** and **9**) could have an additional interactions between them and the side of the active site funnel and this may account for their tighter binding or conversion with higher catalytic efficiency.

In summary, a panel of structurally diverse 2-APA-CoA esters were efficiently converted by AMACR. Chiral inversion probably occurs in both directions, with stereoselective formation of the CoA ester accounting for the specific *R*- to *S*-inversion *in vivo*.<sup>2–6,8–11</sup> AMACR is highly conserved across species and the pathway is probably common in mammals and other species. Chemoprotective effects of 2-APAs have been previously reported, but their effects were ascribed to binding to p75<sup>NTR</sup> or COX.<sup>26–28</sup> Reduction of AMACR activity is proposed as a treatment for prostate and other cancers and inhibition of activity may be an additional mechanism for the chemopreventive effects of 2-APAs. Use of the *R*-2-APA enantiomer to inhibit AMACR, rather than administering a racemic mixture, would be an example of chiral switching<sup>29</sup> to extend the usefulness of a known drug.

This work was supported by Cancer Research UK. Part of this work was performed for a Nuffield Summer Student Bursary (TJH), a Nuffield Science Bursary (GRS) and a Bath-Shandong Pharmacy & Pharmacology Scholarship project (PJ). This work is dedicated to Mr David K. Lloyd (1936 to 2010). TJW, PJW, AST, MDT and MDL are members of the Cancer Research @ Bath network.

## Notes and references

† Abbreviations used: AMACR 1A,  $\alpha$ -methylacyl-CoA racemase, splice variant 1A; 2-APA, 2-arylpropionic acid; CoA, coenzyme A; COX, cyclooxygenase; MCR,  $\alpha$ -methylacyl-CoA racemase (*M. tuberculosis*).

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