Unexpected stereoselective exchange of straight-chain fatty acyl-CoA α-protons by human α-methylacyl-CoA racemase 1A (P504S)†

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α-Methylacyl-CoA racemase (AMACR;† P504S) catalysed exchange of straight-chain fatty acyl-CoA α-protons. One α-proton was removed in each catalytic cycle, with the pro-S proton preferred. This reaction was most efficient for straight-chain substrates with longer side-chains. 2-Methyldecanoyl-CoA underwent α-proton exchange 3× more efficiently (as judged by $K_{cat}/K_m$) than decanoyl-CoA.

Branched-chain fatty acids, e.g. phytanic acid (3R/S,7R,11R,15-tetramethylhexadecanoic acid), are important components of the human diet and are also used as drugs e.g. ibuprofen.1,2 Phytanic acid is derived from the phytol side chain of chlorophyll A and is abundant in red meat and dairy products.3 High amounts of phytic acid in the diet are a risk factor for prostate cancer,4,5 the most common male-specific cancer. The presence of the 3-methyl group in phytanic acid prevents β-oxidation, and it is processed as its CoA ester by peroxisomal α-oxidation to give pristanic acid (2R/S,6R,10R,14-tetramethylpentadecanoic acid). Pristanic acid is metabolised as its CoA ester by β-oxidation in peroxisomes and subsequently in mitochondria for chain-shortened derivatives.2,3,6 The β-oxidation pathway only oxidises α-methyl fatty acyl-CoA esters with 2S configuration,2,7 but 2R-methylacyl-CoA esters are produced during the degradation of phytic acid and other endogenous fatty acids.

Chiral inversion of these R-2-methylacyl-CoA esters is catalysed by the enzyme α-methylacyl-CoA racemase (AMACR) (Scheme 1).1,2 and proceeds by removal of an α-proton to give an enol/enolate intermediate followed by non-stereoselective reprotonation.1 The enzyme has two bases within the active site, the His-122/Glu-237 pair and Asp-156, indicating that the α-protons exchanged during each catalytic event? (2) If only one α-proton is exchanged, is the reaction stereoselective? (3) Is the presence of substrate straight-chain fatty acyl-CoA esters likely to interfere with or modulate "conventional" racemase activity of AMACR in vivo?

Initially, decanoyl-CoA 2 was incubated with recombinant human AMACR 1A in buffer containing 2H2O. Decanoyl-CoA 2 was chosen as this is the straight-chain analogue of the previously reported S- and R-2-methyldecanoyl-CoA substrates (1S and 1R).1 Incubations of 2 with active enzyme resulted in a reduction in the peak intensity of the triplet for the α-protons at δ 2.36–2.46 in the 1H NMR spectrum, along with changes in the structure of the β-proton quintet at δ 1.40. Levels of conversion of ca. 35–40% were observed after incubation for 16 h. Incubation of 2,2-2H2-decanoyl-CoA 3 (R1, R2 = 2H) with active AMACR in 1H2O buffer resulted in the appearance of a triplet in the 1H NMR spectrum for the α-protons and changes in the β-protons signal from a triplet into a quintet. High levels of conversion were observed, indicating that the $\alpha^{-1}H \leftrightarrow \alpha^{-2}H$ exchange reactions are efficiently catalysed by AMACR in both directions. These
changes were not observed in negative controls lacking active enzyme.

To determine whether one or both α-protons could be exchanged by AMACR in each catalytic cycle, incubations were carried out with 2-[13C]-decanoyl-CoA in D2O buffer. This resulted in exchange of the α H for deuterium, as judged by 13C NMR spectroscopy. At t = 0, the spectrum of the incubation mixture showed only a strong singlet at δ 37.65 arising from the 13C carrying only 2 × 1H. The 13C NMR spectrum at early reaction time points also contained a triplet at δ 37.25, with peak-height ratio 1 : 1 : 1, indicating that only one deuterium was directly attached to the 2-13C (Fig. 1). Only at very high levels of conversion was a small quintet (corresponding to 2-13C2H2) seen in this region of the spectrum. These observations are only consistent with exchange of one α-proton at each “visit” of the substrate to the active site of the enzyme; the slow formation of 2-13C2H2-decanoyl-CoA occurs from a second “visit” to the enzyme active site by 2-13C2H1-decanoyl-CoA 5. This result was initially surprising since the rate of exchange of protons was expected to be much faster than that of release of product, and hence exchange of both α-protons was expected. However, the proposed catalytic mechanism of AMACR1,8 is consistent with substitution of a single proton. In this mechanism, one of the α-protons is removed by either Asp-152 or Glu-237/His-122, depending on whether the pro-R or pro-S proton is removed. The deprotonated intermediate can then react either with the proton on the initial base (to give back an unlabeled acyl-CoA) or with a deuterium on the other base. Extraction of the second α-proton can only take place if proton transfer occurs between the two catalytic bases or between the bases and bulk solvent before release of product.

The stereochemical course of this single substitution with deuterium was then investigated. Decanoyl-CoA 2 was incubated with active enzyme until ca. 60% exchange of the α-protons with deuterium had occurred. Following quenching of the reaction, the CoA ester mixture was hydrolysed and the resulting acids were derivatised with R-2-mandelate methyl ester. In unlabelled methyl O-decanoyl-S-mandelate, the 2-protons of the decanoyl unit are inequivalent and resonate at different frequencies in the 1H NMR spectrum, with the pro-S-proton signal centered at δ 2.29 and the pro-R-proton at δ 2.33. These assignments were made by analogy with the findings of Parker14 who showed that the pro-R 2-H of the aliphatic acyl group of a range of methyl O-(fatty-acyl)-S-mandelates always resonated at higher frequency than did the corresponding pro-S 2-H. Assignments of the more upfield and more downfield signals are reversed for chiral derivatization with methyl R-mandelate. Schwab and Lin15 also used this method to establish the absolute configuration of synthetic 2-13H1-decanoic acid. 1H NMR analysis of our derivatised product mixture 6 showed that integral of the signal at δ 2.33 (from the 2S-proton of the decanoic acid)14 was much smaller than that of the signal at δ 2.29 (from the 2R-proton) (Fig. 2). Comparison of the integrals with those for the OMe signal of the methyl mandelate unit showed that the 2-pro-S proton had been replaced approximately five times more often than the 2-pro-R proton in the decanoyl-CoA 2. It is not clear whether this result arises from stereoselective deprotonation of the acyl-CoA substrate or stereoselective reprotonation of the enol/enate intermediate.

The possibility that binding of straight-chain acyl-CoA substrates could interfere with branched-chain fatty acid metabolism was then investigated. Such, the catalytic efficiency of proton exchange by AMACR with S-2-methyl-decanoyl-CoA 1S and decanoyl-CoA 2 was determined by Michaelis–Menten kinetics. The known substrate S-2-methyl-decanoyl-CoA 1S gave the following kinetic parameters: $K_m = 614 \, \mu M$; $V_{max} = 88.7 \, \text{nmol min}^{-1} \, \text{mg}^{-1}$; $k_{cat} = 0.07 \, \text{s}^{-1}$; $k_{cat}/K_m = 114 \, \text{M}^{-1} \, \text{s}^{-1}$ at 30 °C, consistent with previous reports.1 Kinetic analysis of decanoyl-CoA 2 substrate with the AMACR showed non-competitive substrate inhibition at higher substrate concentrations, probably due to incomplete dissolution in the buffer or formation of micelles. The following kinetic parameters were estimated: $K_m = 225 \, \mu M$; $V_{max} = 10.6 \, \text{nmol min}^{-1} \, \text{mg}^{-1}$.
Exchange of $\alpha^{-1}\text{H}$ for $^2\text{H}$ in straight-chain acyl-CoAs of differing chain lengths. Error bars are ± one standard deviation ($n = 2$).

$k_{\text{cat}} = 0.0084 \text{ s}^{-1}$; $k_{\text{cat}}/K_m = 37.4 \text{ M}^{-1} \text{ s}^{-1}$. Therefore, the S-2-methyldecanoyl-CoA substrate appears to be exchanged ca. 3-fold more efficiently than decanoyl-CoA, as judged by $k_{\text{cat}}/K_m$. However, the non-Michaelis-Menten behaviour of decanoyl-CoA means this difference could be significantly larger. It therefore seems likely that $\alpha$-proton exchange of straight-chain fatty acyl-CoA esters by AMACR is not physiologically significant in the presence of branched-chain substrates.

The effect of chain-length on the rates of proton exchange of acyl-CoA substrates by AMACR was then investigated by incubation of acyl-CoAs of varying chain lengths with the enzyme for 16 h at 30 °C in buffer containing $^2\text{H}_2\text{O}$. Acetyl-CoA was not significantly converted ($<1\%$ conversion). The extents of exchange of the $\alpha$-protons for deuterium for C4–C10 straight-chain substrates were measured by $^1\text{H}$ NMR (Fig. 3). Increasing the length of the side-chain of the acyl-CoA ester increased the extent of conversion. Butanoyl-CoA was exchanged to $<5\%$, whilst pentanoyl-CoA, hexanoyl-CoA and heptanoyl-CoA were exchanged to 10–25%. The greatest levels of exchange (ca. 40%) were observed for octanoyl-CoA and decanoyl-CoA. Conversion of S-2-methyldecanoyl-CoA was >95% under the same conditions. This apparent dependence of the binding and turnover of the substrates on the chain-length is consistent with substrate binding by hydrophobic interactions with the enzyme. Interestingly, the crystal structures of MCR with acyl-CoA ligands bound show that the side-chain of the substrate interacts with a methionine-rich hydrophobic region at the entrance of the active site.

Conversion of 2-methylpropanoyl-CoA (isobutyryl-CoA) by AMACR was also investigated. Only ca. 1% exchange of $^1\text{H}$ to $^2\text{H}$ was observed under these assay conditions, compared to $<5\%$ for butanoyl-CoA. These two substrates have the same number of carbon atoms and differ only in length of side-chain and in that the former is a branched-chain substrate. Thus, the presence of a methyl group appears to increase the efficiency of catalytic conversion of longer chain substrates (2-methyldecanoyl-CoA vs. decanoyl-CoA) but appears to have little effect on catalytic efficiency with short-chain substrates.

In summary, this communication demonstrates that straight-chain fatty acyl-CoA esters are able to bind to recombinant human AMACR-1A and undergo deprotonation and reprotonation events. Only one of the two $\alpha$-protons is exchanged in each AMACR catalytic cycle and the enzyme has some degree of stereoselectivity. The origin of this stereoselectivity merits further investigation. These results also reveal new details about the catalytic mechanism and substrate binding characteristics of human AMACR-1A. Moreover, this appears to be the only example of a racemase enzyme catalysing proton-exchange in a non-racemisable substrate.

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Notes and references

† Abbreviations used: AMACR, $\alpha$-methylacyl-CoA racemase; MCR, M. tuberculosis homologue of AMACR.