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Journal Title: Journal of Biological Chemistry
Volume: Volume 289, Number 21
Publisher: American Society for Biochemistry and Molecular Biology |
2014-05-23, Pages 14941-14954
Type of Work: Article | Final Publisher PDF
Publisher DOI: 10.1074/jbc.M113.514646
Permanent URL: https://pid.emory.edu/ark:/25593/rmp3g

Final published version: http://dx.doi.org/10.1074/jbc.M113.514646

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Accessed October 27, 2017 2:34 PM EDT
Structural Basis for Ligand Regulation of the Fatty Acid-binding Protein 5, Peroxisome Proliferator-activated Receptor β/δ (FABP5-PPARβ/δ) Signaling Pathway*

Received for publication, September 7, 2013, and in revised form, February 27, 2014. Published, JBC Papers in Press, April 1, 2014, DOI 10.1074/jbc.M113.514646

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Background: Intracellular lipid-binding proteins stimulate lipid-induced gene expression.

Results: Fatty acid-binding protein 5 (FABP5) uses a molecular switch that controls nuclear import when complexed with activating fatty acids.

Conclusion: FABP5 is tuned to selectively stimulate peroxisome proliferation-activated receptor β/δ transactivation in response to specific fatty acids based on their structural features.

Significance: FABPs provide a second level of regulatory control of nuclear receptor-mediated lipid signaling.

Fatty acid-binding proteins (FABPs) are a widely expressed group of calyccins that play a well established role in solubilizing cellular fatty acids. Recent studies, however, have recast FABPs as active participants in vital lipid-signaling pathways. FABP5, like its family members, displays a promiscuous ligand binding profile, capable of interacting with numerous long chain fatty acids of varying degrees of saturation. Certain “activating” fatty acids induce the protein’s cytoplasmic to nuclear translocation, stimulating PPARβ/δ transactivation; however, the rules that govern this process remain unknown. Using a range of structural and biochemical techniques, we show that both linoleic and arachidonic acid elicit FABP5’s translocation by permitting allosteric communication between the ligand-sensing β2 loop and a tertiary nuclear localization signal within the α-helical cap of the protein. Furthermore, we show that more saturated, non-activating fatty acids inhibit nuclear localization signal formation by destabilizing this activation loop, thus implicating FABP5 specifically in cis-bonded, polyunsaturated fatty acid signaling.

LCFAs,3 in addition to serving as a structural component and energy source of the cell, participate in cellular signaling by

modulating the activity of a group of nuclear receptors known as the peroxisome proliferation-activated receptors (PPARs) (1–6). Because of the large number of target genes affected by this family of ligand-regulated transcription factors, LCFAs play a critical role in a variety of cellular processes and their related pathophysiology, ranging from metabolic defects to cell differentiation and cancer progression (7, 8). However, the relative insolubility of these molecules makes them reliant upon a class of transport proteins, the FABPs, to exert their signaling effects (9–11).

There are nine known FABP members in mammals, each ~14–15 kDa in size with orthologs found throughout the animal kingdom (12). Although they exhibit a wide range of sequence identity (~20–70%), all form a twisted β-barrel, composed of 10 anti-parallel β-strands arranged into two orthogonal β-sheets, with a helix-turn-helix lid covering the ligand-binding site (10–12). As members of the intracellular lipid-binding protein (iLBP) family, they have traditionally been thought to be involved in the solubilization/protection of their various hydrophobic cargoes, facilitating ligand movement via passive diffusion between the various compartments of the cell (13, 14). Increasingly, however, FABPs are emerging as specific mediators of precise signaling pathways. For instance, FABP1 facilitates the polyunsaturated fatty acid and fibrate-induced transactivation of PPARα, via direct interaction with the nuclear receptor’s ligand binding domain (15–17). A similar role has been observed with FABP4, whereby its ligand-mediating dimerization state governs nuclear import and subsequent ligand delivery to PPARγ (18, 19). Recent findings have even revealed FABPs to be the once enigmatic N-acylthanolamine honestly significant difference; ANOVA, analysis of variance; PoA, palmitoleic acid; iLBP, intracellular lipid-binding protein; DSm, double-switch mutant; SpA, sapienic acid; PA, palmitic acid; NES, nuclear export signal; PDB, Protein Data Bank; HDX, hydrogen deuterium exchange; EGFP, enhanced green fluorescent protein; h, human; 1,8-ANS, 1-anilinonaphthalene-8-sulfonic acid; CRBP-I, cellular retinol-binding protein I; CRABP-II, cellular retinoic acid-binding protein 2.
Structural Basis for Ligand-driven Activation of FABP5

“transporter,” responsible for endocannabinoid cellular uptake, hydrolysis, and PPARα activation (20, 21).

FABP5 (E-FABP, KFABP, and malf), first characterized almost 20 years ago in keratinocytes, is one of the most ubiquitously expressed proteins in its class, and it can be found across a broad spectrum of tissue/cell types such as the epidermis, adipose, macrophages, mammary glands, brain, kidney, liver, lung, heart, skeletal muscle, and testis (10, 12, 22). A member of the iLBp subfamily IV, FABP5 binds a wide array of ligands in a 1:1 ratio, including fatty acids and fatty acid metabolites spanning 10–22 carbons in length with various saturation states, as well as the vitamin A metabolite all-trans-retinoic acid and numerous synthetic drugs and probes (10, 23–25). It has also been found to be involved in a range of pathologies, including the metabolic syndrome (26, 27), atherosclerosis (28), cancer (29–33), and potentially certain neurodegenerative diseases (34).

Work conducted by Tan et al. demonstrated the ability of FABP5 to specifically enhance the transactivation of PPARβ/δ, whose known gene targets are involved in cellular glucose and lipid homeostasis (35–37), differentiation (38, 39), and resistance to apoptosis (39, 40). Despite FABP5’s promiscuous binding profile, only a subset of fatty acids and other ligands have been shown to result in the protein’s nuclear translocation, where it is thought to engage PPARβ/δ, allowing for the channelling of ligand into the nuclear receptor’s binding pocket (18). Although previous structural studies have shed considerable light on the role of FABP4 in PPARγ signalling (19, 41), the mechanism underlying select lipid activation (e.g. nuclear translocation) of FABP5 remains unknown. Using a combination of x-ray crystallography, hydrogen deuterium exchange (HDX)-mass spectroscopy, and biochemical and cellular approaches, we have established the presence of a ligand-sen-
Cell Localization Assay—COS-7 cells were grown on 10-cm plates in DMEM (Invitrogen) supplemented with 10% fetal bovine serum (FBS) at 37 °C and 5% CO2. At ~60% confluency, polyethyleneimine (Polysciences) was used to transfect cells with 5 µg of pEGFP-N3 vector harboring full-length hFABP5WT, hFABP5NLSm, hFABP5NESm, or hFABP5DSm, with the DNA-PEI complex being removed 6–8 h after exposure. The following day, cells were checked for fluorescent protein expression and then transferred to Lab-Tek II Chamber Slides (Thomas Scientific catalog no. 154526) in DMEM buffer containing 5% charcoal/dextran-stripped FBS. Twenty four hours post-transfer, cells were exposed to 10 µM fatty acid ligand solubilized in 0.1% EtOH for 30 min at 37 °C, washed three times with ice-cold PBS, fixed with 4% paraformaldehyde, and stained with DAPI. Slides were imaged using a Zeiss LSM510 META Upright confocal microscope (×40/1.3 Oil differential interference contrast objectives) employing Zeiss Zen2009 acquisition software, with both nuclear focusing and enhanced green fluorescent protein (EGFP) imaging conducted at an optical slice of 0.9 µm. Nuclear and cytoplasmic EGFP fusion protein fluorescence intensities were quantified using ImageJ, and the calculated nuclear/cytoplasmic ratios were plotted in Prism 5 (GraphPad Inc., La Jolla, CA). Statistical significance was determined by one-factor ANOVA, with individual comparisons made with Tukey’s honestly significant difference (HSD) post hoc tests.

Ligand Binding Assays—Ligand binding was measured via competition of 1-anilinonaphthalene-8-sulfonic acid (1,8-ANS), which displays increased fluorescence when exposed to a hydrophobic environment (51). In brief, both wild-type and mutant hFABP5 were expressed and purified to homogeneity as described above and dialyzed in PBS (pH 7.4). Binding affinity (Ki) was derived by monitoring maximal fluorescence intensity of a constant concentration of 500 nM 1,8-ANS with increasing protein concentrations ranging from 20 nM to 424 µM. Blank measurements obtained from protein-only samples were subtracted at each protein concentration tested to obtain the final values. Competition assays were then performed in which the protein was held at a constant concentration of 500 nM (1 µM for the FABP5NLSm palmitic acid competition), with 1,8-ANS also being held constant at either 5 µM (for hFABP5WT and hFABP5DSm) or 10 µM (for hFABP5NLSm) in the presence of increasing fatty acid concentrations from 10 nM to 200 µM. Blanks consisting of 1,8-ANS and fatty acid in the absence of protein were subtracted at each ligand concentration tested. The resulting fluorescence values were used to calculate a Ki value for the fatty acid of interest. Data were collected at 30 °C on a BioTek Synergy plate reader using an excitation filter of 380/20 nm and an emission filter of 460/40 nm and processed in GraphPad Prism 5. Statistical significance was determined by one-factor ANOVA, and individual comparisons were made with Tukey’s HSD post hoc tests.

In-cell Activation Assays—MCF-7 cells were transferred to 96-well plates, where they were grown and maintained in high glucose DMEM containing L-glutamine, sodium pyruvate, and phenol red (Invitrogen), supplemented with 10% charcoal/dextran-stripped FBS (Invitrogen), and 1% penicillin/streptomycin (Culture Buffer). One hundred ng well−1 pSG5 vector harboring full-length mouse PPARβ/δ receptor, 100 ng well−1 PPAR-response element-driven firefly luciferase reporter (PPAR-response element X3-TK-luc), and 20 ng well−1 constitutive Renilla luciferase reporter (pRLtk) in the presence or absence of 25 ng well−1 wild-type or mutant variant human FABP5 cloned into the pcMV-Tag2B vector was added to FuGENE HD in Opti-MEM (Invitrogen). This solution was diluted with Culture Buffer (–antibiotic) to a final concentration of 2.2–2.45 µM total DNA. 100 µl well−1 of this solution was used to transfect 70–90% confluent cells overnight. Cells were then treated in sextuplicate with 1–100 µM fatty acid ligand or vehicle (ethanol) in high glucose DMEM containing only L-glutamine and 1% penicillin/streptomycin for 24 h (final working ethanol concentration 0.1%), and assayed with Dual-Glo luciferase substrate (Promega). Firefly activity was divided by Renilla activity to account for cell number, viability, and transfection efficiency, and graphs were generated in GraphPad Prism 5. Statistical significance was determined by either one- or two-factor ANOVA, and individual comparisons were made with Tukey HSD or Bonferroni post hoc tests.

Protein Unfolding Assay—Pure hFABP5WT and hFABP5NESm (1 µM, PBS) was exposed to increasing concentrations of guanidinium hydrochloride, and the resulting shift in peak intrinsic fluorescence intensity was measured using a Shimadzu RF-5301PC spectrofluorophotometer at an excitation wavelength of 280 nm with a 5-nm spectral bandwidth. Values were fitted using a four-parameter logistic equation, and the calculated fluorescence shift midpoints were compared via unpaired t test with Welch’s correction for unequal variances in GraphPad Prism 5.

HDX—Solution-phase amide HDX was carried out with a fully automated system as described previously (52). Briefly, 4 µl of sample consisting of 10 µM protein and 100 µM ligand in PBS (pH 7.4) was diluted to 20 µl with D2O-containing HDX buffer and incubated at 25 °C for 10, 30, 60, 900, or 3600 s. Following on exchange, back exchange was minimized, and the protein was denatured by dilution to 50 µl in a low pH and low temperature buffer containing 0.1% (v/v) TFA in 5 M urea (held at 1 °C). Samples were then passed across an immobilized pep- sin column (prepared in house) at 50 µl min−1 (0.1% v/v TFA, 15 °C); the resulting peptides were trapped on a C8 trap cartridge (Hypersil Gold, Thermo Fisher). Peptides were then gradient-eluted 4–40% (w/v) CH3CN, 0.3% (w/v) formic acid over 5 min at 2 °C across a 1 × 50-mm C18 HPLC column (Hypersil Gold, Thermo Fisher), and electrospayed directly into an Orbitrap mass spectrometer (LTQ Orbitrap with ETD, Thermo Fisher). Peptide ion signals with a MASCOT score of >20 were used if they had no ambiguous hits using a decoy database. Average percent deuterium incorporation was calculated with in-house developed software (53). Each envelope was corrected for back-exchange assuming 70% recovery and accounting for the known deuterium content of the on-exchange buffer. To quantify the difference in exchange rates, we calculated the average percent deuterium uptake for wild-type (WT) FABP5/PoA following 10, 30, 60, 900, and 3600 s of on-exchange by averaging percent deuterium incorporation across all time points.
Structural Basis for Ligand-driven Activation of FABP5

RESULTS

Overall Structure and Oligomerization Status of Apo- and Holo-FABP5—To elucidate the molecular mechanisms driving ligand-specific FABP5 activation, we determined crystal structures of apo-FABP5 and FABP5 in complex with LA, an ω-6 polyunsaturated pan-PPAR fatty acid agonist that has been shown to trigger FABP5’s nuclear translocation (18). Because recombinant FABP5 co-purifies with E. coli LCFAs, delipidation/denaturation of the protein followed by refolding was performed prior to LA exposure and subsequent crystallization (42, 54). The structure of apo-FABP5 was solved in the P4_2_2_2 space group at high resolution (1.67 Å), with the asymmetric unit comprised of a FABP5 monomer adopting the canonical iLBPs (Fig. 1a) (54, 55). Interestingly, crystals of the FABP5-LA complex grew only in the P3_2_1_2 space group, with the resulting 2.6-Å structure revealing four copies of protein in the asymmetric unit (Table 1 and Fig. 1b). Because modulation of dimer interface is thought to account for the ligand-specific activation of FABP5, size exclusion chromatography of both apoprotein (Bligh and Dyer delipidated and refolded) and FABP5 purified in the presence of saturating amounts of LA reveals that FABP5 is monomeric in both the liganded and unliganded state (Fig. 1c). Additionally, dynamic light scattering conducted on untreated recombinant protein indicates that FABP5 exists solely in a monomeric population (data not shown), despite the presence of various bacterial LCFAs, suggesting that fatty acids do not alter the oligomerization state of the protein.

Linoleic Acid Binds FABP5 in Two Distinct Conformations—The FABP5-LA interactions are in general very similar to those previously described by Hohoff et al. (54) in their analysis of E. coli fatty acid. The carboxylic headgroup of LA forms a salt bridge with Arg-129, as well as a hydrogen bond with the hydroxyl moiety of Tyr-131. An additional hydrogen bond interaction is observed between LA and Arg-109 via an ordered water molecule (Fig. 2a). The alkyl tail of the fatty acid is largely stabilized by van der Waals interactions made with the hydrophobic side chains of multiple amino acids that line the binding pocket, including Cys-120. Intriguingly, whereas all previous structural studies of FABP5 have shown this amino acid to participate in disulfide bond formation with

Table 1

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* Data were collected from a single crystal; values in parentheses are for highest resolution shell.

FIGURE 1. Structural overview of apo- versus LA-bound FABP5. a, tertiary structure of apo-FABP5. Unbound protein adopts the familiar β-barrel fold capped by an α-helical lid, with a 310 helix at the N terminus. b, asymmetric unit of the FABP5-LA crystal, composed of four copies of ligand-bound protein. c, overlay of size exclusion chromatographs for apo- (orange) and LA-complexed (green) FABP5. Standard consisting of 1.35-, 17-, 44-, 158-, and 670-kDa markers is in black.
Cys-127, electron density reveals the unequivocal presence of both amino acids in their sulfhydryl forms within all four monomers of LA-bound FABP5 (Fig. 2b) (54, 55). In contrast, the apoprotein contains a mixture of cysteine-cystine forms (Fig. 2c). Because the *E. coli* fatty acid in the Hohoff *et al.* (54) structure could only be modeled at 50% occupancy, we conclude that the absence of a disulfide bridge within FABP5-LA is the result of the ligand being fully bound, and it likely helps to accommodate the \(-191 \text{ Å}^3\) increase (averaged across all four FABP5-LA monomers) in ligand pocket volume as compared with apoprotein (49).

Visualization of the water network within the binding pocket of the apo- and LA holo-proteins reveals a much higher number of ordered water molecules located within the top half of the \(\alpha\) helix nearer the \(\beta\) barrel nearer the \(\alpha\) helix than in the bottom half closer to the proteins’ termini. Although the presence of ligand is responsible for partial rearrangement of this network, waters 2, 7, 15, 31, 38, and 82 in apo-FABP5 remain virtually unaltered between the two structures, suggesting their importance in maintaining binding pocket architecture. Conservation of such a relatively large number of FABP5’s ordered waters likely reflects the protein’s heavy reliance upon enthalpic versus entropic contributions in binding fatty acids, a property common to the protein class (56).

Although monomers C and D bind LA in the traditional U-conformation, most commonly seen for fatty acids within the binding pockets of iLBPs subfamily IV members (FABP3–5 and –7–9), LA adopts a bent or “L” conformation within the pockets of monomers A and B (purple) versus monomers C and D (green) in the FABP5-LA crystal structure (see Fig. 1b).

**FIGURE 2. Analysis of FABP5 ligand binding pocket and LA’s bound conformations.**

(a) LA is held within FABP5 via a salt bridge and hydrogen bonding with its carboxylic headgroup and hydrophobic interactions with its alkyl tail. (b) and (c), Cys-120 and Cys-127 are unequivocally in their sulfhydryl forms in the presence of LA (b), yet are able to adopt either free or disulfide-bond states within apo-FABP5 (c). The simulated annealing \(\text{Fo} - \text{Fc}\) omit map of electron density was contoured at 2.5\(\sigma\) for a, and 2\(\text{Fo} - \text{Fc}\) electron density maps were modeled at 1\(\sigma\) for b and c. d, conformation of LA when bound to monomers A and B (purple) versus monomers C and D (green) in the FABP5-LA crystal structure (see Fig. 1b).
bind in a manner that disrupts the protein’s β2 portal loop, similar to LA’s L-conformation (41, 57). Thus, it was reasoned that LA’s U-conformation correlates to its FABP5-activating form, whereas the L-conformation represents a nonactivating binding mode. Based on this rationale, FABP5-activating fatty acids could be predicted based on their propensity to adopt a similar U- versus L-configuration when bound to the protein.

To test this hypothesis, four lipids in addition to LA were selected for functional analysis as follows: arachidonic acid (AA), a 20-carbon polyunsaturated ω-6 fatty acid known to activate PPAR (4); PoA, a 16-carbon monounsaturated ω-7 fatty acid; sapienic acid (SpA), a 16-carbon monounsaturated ω-10 fatty acid; and the fully saturated 16-carbon palmitic acid (PA) (Table 2). Assuming that their ability to favor an activating binding mode within FABP5 correlates to their natural degree of conformational curvature, AA was predicted to be an FABP5-activating fatty acid, similar to LA, although PoA, SpA, and PA were predicted nonactivators.

To gauge an appropriate range of ligand concentrations needed for FABP5 activation assays, we determined the affinity of FABP5 for the five fatty acid candidates by testing their ability to displace the fluorophore 1,8-ANS from the lipid binding pocket, as described previously (51). The binding constants obtained for AA, LA, PoA, and PA (Table 3) are somewhat higher than those calculated previously using a similar technique, falling within the range of affinities measured via the Lipidx method (24, 54). Additionally, our results indicate that FABP5 binds AA significantly worse than the other candidates, while exhibiting a relatively high affinity for PA (Fig. 3a). Thus, in our hands, the binding preference of FABP5 approximately correlates with fatty acid aqueous solubility, a phenomenon known as the “solubility hypothesis” that has been used to characterize the ligand affinity trends of proteins throughout the group (58, 59).

We then examined the proclivity of these fatty acids to drive the FABP5 nuclear localization. Endogenous FABP5 localizes primarily to the cytoplasm; however, overexpression of the pro-
tein combined with the innate ability of EGFP to partially localize to the nucleus results in the presence of FABP5-EGFP construct throughout the cell, even in the absence of ligand (Fig. 3b, top panel) (25, 60). Therefore, to obtain a robust measurement of ligand-induced nuclear localization, we quantified the ratio of nuclear fluorescence to cytoplasmic fluorescence, and we averaged this value for 30 cells per condition. LA treatment resulted in a statistically significant increase in nuclear localization compared with 0.1% ethanol (vehicle) treatment only, thus confirming LA as an activating ligand of FABP5 (Fig. 3b). Additionally, AA exposure led to the highest increase in nuclear/cytoplasmic average fluorescence, whereas PA, SpA, and especially PoA, had no significant effect. These results designate AA as a newly discovered FABP5 activator.

As FABP5 has been shown to participate in a direct signaling pathway with PPARβ/δ (18), we investigated the protein's ability to enhance AA- and LA-induced PPARβ/δ activation. To reduce background, assays were carried out in MCF-7 cells, which produce very low levels of endogenous FABP5. Verification of PPARβ/δ activation as a suitable metric for fatty acid signaling was first conducted in cells overexpressing receptor (Fig. 3b). FABP5 overexpression augmented AA agonism of PPARβ/δ at ligand concentrations of 40–100 μM, with the effect becoming more pronounced at higher concentrations (Fig. 4b). PPARβ/δ activation in the presence of LA was also enhanced by overexpression of FABP5, the effect being first observed at 60 μM fatty acid and gradually diminishing at 80 and 100 μM (Fig. 4c). In contrast, FABP5 did not enhance PoA- nor SpA-induced receptor activation, even leading to a dampening of response at 100 μM PoA (Fig. 4, d and e).

**FABP5 Contains a Ligand-sensitive NLS within Its α-Helical Lid**—We next set out to determine the structural mechanism responsible for the ligand-specific nuclear translocation of FABP5. FABP5 does not harbor a classical NLS within its primary sequence. However, studies conducted on the iLBPs cellular retinoic acid-binding protein 2 (CRABP-II) (61) and FABP4 (19) prompted us to search for a tertiary, or cryptic, NLS within the three-dimensional structure. As the vast majority of all known NLS motifs are highly basic in nature (62), we created an electrostatic potential map of FABP5, which clearly displays a large patch of positive charge located on the surface of the protein's α-helical cap. Within this region, we identified two well ordered, solvent-exposed lysines (Lys-24 and Lys-34) and an arginine (Arg-33), homologous to the NLS residues of
CRABP-II and FABP4 (shown in overlay with monomer C of FABP5-LA) (Fig. 5a).

To test the role of these residues in nuclear import, we created FABP5NLSm, in which Lys-24, Lys-34, and Arg-33 were substituted with alanines. The substitutions had no impact on expression, purification, or stability (data not shown). All fatty acid candidates were able to successfully compete 1,8-ANS from the protein’s binding pocket, although the NLS mutant exhibited reduced binding affinity for AA and PA (Fig. 5, b and c, and Table 3). Cell localization assays reveal that FABP5NLSm is unable to translocate to the nucleus in the presence of the activators AA or LA (Fig. 5d). Similarly, FABP5NLSm was unable to enhance AA-induced activation of PPARβ/δ at any of the selected ligand concentrations, instead suppressing PPARβ/δ transactivation at exposure levels of 60, 80, and 100 μM (Fig. 5e). As these concentrations are 6.4-, 8.5-, and 10.7-fold, respectively, over the ligand’s $K_i$ value, it is extremely unlikely that such effects are attributable to the mutant’s altered AA binding ability. Collectively, these data indicate that a cryptic NLS, located on the α-helical cap of the fatty acid binding pocket, is required for ligand-dependent activation.

**NES Equivalent Residues of FABP5 Are Necessary for Protein Stability**—FABP4 has been shown to possess a tertiary NES composed of three leucine residues (Leu-67, Leu-87, and Leu-92) located at the edge of its α-barrel farthest from its α-helix lid (Fig. 6a) (19). Given their structural similarity, we reasoned that FABP5 might also have a tertiary NES that is formed from residues equivalent to those that belong to the NES of FABP4. A

![FIGURE 5: Tertiary nuclear localization signal of FABP5.](image_url)

**Figure 5.** Tertiary nuclear localization signal of FABP5. a, surface potential of FABP5 bound to LA in the active “U” conformation. Units are in multiples of 26.7 mV ($k_B$, Boltzmann’s constant; $T$, temperature; $e$, electron charge). Overlay of activated FABP5-LA (green) with FABP4 bound to 1,8-ANS (yellow, Protein Data Bank code 2ANS) reveals FABP5’s homologous tertiary NLS residues as follows: Lys-24, Lys-34, and Arg-33. b and c, FABP5NLSm was able to bind 1,8-ANS (b), which could be displaced from the binding pocket by all fatty acid candidates tested (only AA is shown (c)) (n = 6). d, neither LA nor AA exposure (10 μM) resulted in significant nuclear translocation of EGFP-FABP5NLSm (n = 30), as determined by one-factor ANOVA. e, expression of FABP5NLSm resulted in subdued PPARβ/δ activation at AA concentrations of 60, 80, and 100 μM (n = 6). Statistical analysis was performed using two-factor ANOVA, with Bonferroni post hoc tests used for individual comparisons. ****, $p = 0.0001$. The mean ± S.E. is shown for all data points.
structural overlay of the two proteins reveals the conservation of two of the three leucines (residues 69 and 94) with the third being Phe-89 in FABP5 (Fig. 6b), a less common but still acceptable NES amino acid substitution because of its ability to preserve the overall hydrophobic character of the signal (63). However, expression of EGFP-tagged FABP5NESm, in which the three residues had been mutated to alanines, resulted in the presence of fluorescing puncta located within both the nuclei and cytoplasm of COS-7 cells (Fig. 6c), suggesting that the mutations may affect structural integrity.

To address this concern, we carried out guanidinium hydrochloride unfolding of both FABP5NESm and wild-type protein, using maximal intrinsic fluorescence intensity wavelength as an indicator of tertiary structure. The unfolding curve of unaltered FABP5 is sigmoidal in nature with the protein exhibiting an average maximum fluorescence wavelength of 331 nm in the absence of denaturant. In contrast, FABP5NESm’s curve appears substantially more linear, with an average maximum fluorescence wavelength of nearly 335 nm at 0M guanidinium hydrochloride, indicating a partially denatured resting state of the mutant protein (Fig. 6d). The concentration of guanidinium hydrochloride necessary to induce the midpoint in maximal intensity wavelength shift varied significantly between proteins, at 1.64 ± 0.03 M for wild-type FABP5 and 0.70 ± 0.30 M for FABP5NESm (Fig. 6e). Therefore, because mutating residues 69, 94, and 98 reduced protein stability, we were unable to positively confirm the presence or identity of the NES.

Ligand-specific Dynamics between β2 Loop and α2 Helix Drives Tertiary NLS Formation—Having identified the cryptic NLS within FABP5, we finally directed our efforts to elucidating a possible driving force responsible for ligand-specific NLS formation. The β-C-D, or β2 loop, along with the βE-F loop and α2 helix together constitute the portal domain (64), a feature common throughout the FABPs that is hypothesized to gate ligand access to and from the binding pocket (56) and that has been shown to display structural mobility within FABP5 (55). Analysis of the backbone temperature values for apo-FABP5 lends support for this domain’s relatively more labile nature, with the average B-factors of the β2 helix (20.95 Å²) and especially the β2 loop (28.42 Å²) considerably higher than that for the entire protein (16.3 Å²) (Fig. 7a). Furthermore, overlay of FABP5-LA in its proposed activated (monomer C) versus inactivated state (monomer B) reveals that, to avoid a collision with L-conformation LA, the backbone of residues 59–61 within the β2 loop must shift away from the rest of the protein body, assuming a conformation in which there is less contact with α2 helix 2 (Fig. 7b).

To probe the dynamics of FABP5 bound to a nonactivator versus activator, we utilized HDX, which provides an unbiased assessment of backbone motion in solution. The difference in percent deuterium uptake revealed weaker protection of residues that compose the α2 helix and β2 loop within FABP5-PoA relative to FABP5-AA, indicating decreased stabilization of these elements (Fig. 7c). Taken together with our crystallo-
graphic data, we hypothesize that the interaction between the α2 helix and the β2 loop via residues Met-35 and Leu-60 determines the activation state of the protein (Fig. 7, b and c). When bound to a fatty acid with a solvent-exposed alkyl tail, the loop must remain open. This breaks contact between Met-35 and Leu-60, destabilizing the ηα2 helix and thereby rendering FABP5 inactive. Conversely, binding to a more compact, sterically constrained fatty acid such as AA allows for loop closure, providing the additional hydrophobic contacts required to stabilize the ηα2 helix. This results in a more coalesced formation of the NLS and likely drives protein activation.

To examine the potential role of Met-35 and Leu-60 as ligand conformation sensing “activation switches,” we reduced their hydrophobic interaction via mutation of both residues to alanines, creating a double-switch mutant of FABP5 (FABP5DSm). These mutations had no major impact on ligand binding in vitro (Fig. 8, a and b, and Table 3), yet HDX analysis reveals that they decrease the stability of the ηα2 helix-β2 loop interface within the mutant protein bound to AA, relative to the wild-type protein AA complex (Fig. 8c). Thus, FABP5DSm does not possess the allosteric coordination that senses and relays information from AA to the NLS. Additionally, comparison of mutant with wild-type protein when both are bound to the nonactivating PoA displays far fewer differences in subsequent deuterium exchange, indicative of largely equal states of loop/helix disruption (Fig. 8d). This effect can also be observed in the HDX analysis of FABP5DSm-PoA relative to FABP5DSm-AA, which, when compared with Fig. 7c, clearly illustrates the mutant’s
severely hampered ability to structurally distinguish activating from nonactivating ligand (Fig. 8e).

Finally, we conducted cellular assays with the double-switch mutant protein to provide biological verification of the results obtained from HDX. Although LA exposure was unable to induce additional FABP5DSm nuclear localization, AA treatment actually resulted in increased cytoplasmic localization (Fig. 9a). Reporter gene assays confirmed a loss in signaling ability of FABP5DSm, with expression of the protein resulting in diminished AA-induced PPAR/β/δ activation at concentrations of 60–100 μM AA (Fig. 9b). These conclusions are further strengthened by the more striking direct comparison of normalized AA dose responses of PPAR/β/δ in the presence of FABP5WT, FABP5NLSm, or FABP5DSm. Data sets were taken from Figs. 4b, 5e, and 9b and were normalized internally by dividing all replicate values by the average value obtained from vehicle treatment only. Statistical analyses were performed using either one-factor (a) or two-factor (b and c) ANOVA, with Tukey HSD (a) or Bonferroni (b and c) post hoc tests used for individual comparisons. **, p ≤ 0.01; ****, p ≤ 0.0001. The mean ± S.E. is shown for all data points.

DISCUSSION

Since the discovery of the first FABP’s by Ockner et al. (65) over 40 years ago, a wealth of data have steadily accumulated regarding the structure and function of this class of proteins (9). Although the vast majority of structural studies have focused on the determinants of stability and ligand binding, almost no attention outside of FABP1 and -4 has been given to the physical mechanisms driving signal propagation and protein-protein interaction (19, 41, 66–68). We have expanded understanding of FABP signaling by identifying the molecular switch that dictates fatty acid-specific activation, whereby the conformation of bound LCFA relays information from what we now term the “activation loop” (βC-D) of the portal region to the protein’s tertiary NLS, consisting of Lys-24, Arg-33, and Lys-34. In this way, FABP5 shares key mechanistic elements from both FABP4 and CRABP-II, yet ultimately undergoes a method of activation different from either. Like FABP4, only certain ligands cause nuclear localization of the protein (18, 41). However, instead of dimer rearrangement driving the cytosolic...
exposure of the NLS, FABP5, like CRABP-II, remains monomeric, with binding of activating ligand resulting in stabilization of the NLS that is necessary for nuclear import (41, 61). Interestingly, although this process can occur in as little as 30–60 min for all three proteins, the ensuing enhancement of nuclear receptor-driven gene transcription is most frequently tested 24 h after ligand introduction (19, 69, 70). This time difference could explain, at least in part, why 10 μM AA and LA are sufficient for our localization assays, but not for FABP5-enhanced transactivation of PPARβ/δ, as ligand degradation and metabolism become more relevant over time.

Sequence alignment in Clustal Omega (71) of all nine human FABP members with other iLBPs known to participate in ligand-mediated signaling reveals that FABP8, a major protein constituent of the peripheral nervous system myelin (72), contains residues homologous to the cryptic NLS present in FABP4 and -5 and CRABP-II, as well as to the pair of bulky/hydrophobic amino acids that constitute the ligand-dependent activation switch (Fig. 10). This raises the possibility that myelin FABP could also undergo directed nuclear localization; however, the same NLS homology is also found within the α helices of the iLBp cellular retinol-binding protein 1 (CRBP-I), where it governs the protein’s retinol-dependent interaction with the transmembrane receptor stimulated by retinoic acid 6 (STRA6) (73). Therefore, the potential of FABP8 to engage in a ligand-driven signaling pathway other than nuclear translocation cannot be discounted. Based on its predicted amino acid sequence (data not shown), the same directed inquiries can also be made for the newly discovered FABP12, although its presence within cells has not been documented beyond the mRNA level (74).

Additionally, we have shown that a single fatty acid can adopt at least two unique conformations within the binding pocket of FABP5. Although FABP-bound fatty acid tail mobility has been noted previously via x-ray crystallography (75), our delineation of an active U-conformation versus inactive L-conformer opens up exciting new possibilities for structure-based drug design. The overexpression of FABP5 has been linked to insulin resistance (26), and its signaling is related to cancer cell survival (25), proliferation (29, 32), and metastasis (31, 33), making the protein an ideal candidate for antagonist development. Theoretically, such compounds could exert their influence via one of several mechanisms of action. The first would be to bind and disrupt the portal region, forcing the activation loop into its inactive state. The second would be to bind completely within the binding pocket, allowing closure of the activation loop and subsequent nuclear translocation of the protein, although the compound itself would be unable to bind PPARβ/δ. The third, and likely most potent, would be to improve the nuclear accumulation of current PPARβ/δ antagonists by optimizing their ability to bind and activate FABP5.

Conversely, our fatty acid binding model can be used for the prediction of additional FABP5 activators. We have demonstrated that the state of unsaturation is one of the major determinants of a fatty acid’s activation potential, presumably due to its effect on U-conformation preference within the binding pocket. Judging from the configurations seen within our structures as well as that published by Hohoff et al. (54), the first 11–13 carbons share a remarkably close alignment regardless of fatty acid type, thereby placing a greater degree of importance for activator differentiation on the cis-double bonds located more distal to the carboxylate headgroup. As both LA and AA were found to be activators, yet PoA (an ω-7 FA) was not, this suggests an intriguing role for FABP5 as a specific mediator for ω-6 and possibly ω-3 fatty acid signaling. Because all unsaturated fatty acids tested, including oleic acid (data not shown), were able to significantly activate PPARβ/δ in the absence of FABP5, the presence of such a secondary control measure likely serves to ensure preferential activation of the nuclear receptor by this or a similar subset of fatty acids.

Acknowledgments—We gratefully acknowledge Alexa Mattheyses, Jason Fritz, and Debbie Martinson (Integrated Cellular Imaging Core, Emory University) and Shuiliang Yu (Case Western Reserve University) for training in microscopy methods, and Katie Doud (Case Western Reserve University) for generous assistance with the PPARβ/δ activation assays. Data for 4LKP were collected at Southeast Regional Collaborative Access Team (SER-CAT) 22-BM beamline at the Advanced Photon Source, Argonne National Laboratory. Use of the Advanced Photon Source was supported by the United States Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract W-31-109-Eng-38.

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Structural Basis for Ligand-driven Activation of FABP5


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Structural Basis for Ligand Regulation of the Fatty Acid-binding Protein 5, Peroxisome Proliferator-activated Receptor β/δ (FABP5-PPARβ/δ) Signaling Pathway

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doi: 10.1074/jbc.M113.514646 originally published online April 1, 2014

Access the most updated version of this article at doi: 10.1074/jbc.M113.514646

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