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Palmitate interaction with physiological states of myoglobin

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ABSTRACT

Background: Previous studies have shown that palmitate (PA) can bind specifically and non-specifically to Fe(III) MbCN. The present study has observed PA interaction with physiological states of Fe(II) Mb, and the observations support the hypothesis that Mb may have a potential role in facilitating intracellular fatty acid transport.
Methods: ^{1}H NMR spectra measurements of the Mb signal during PA titration show signal changes consistent with specific and non-specific binding.
Results: Palmitate (PA) interacts differently with physiological states of Mb. Deoxy Mb does not interact specifically or non-specifically with PA, while the carbonmonoxy myoglobin (MbCO) interaction with PA decreases the intensity of selective signals and produces a 0.15 ppm upfield shift of the PA methylene peak. The selective signal change upon PA titration provides a basis to determine an apparent PA binding constant, which serves to create a model comparing the competitive PA binding and facilitated fatty acid transport of Mb and fatty acid binding protein (FABP).
Conclusions: Given contrasting PA interaction of ligated vs. unligated Mb, the cellular fatty acid binding protein (FABP) and Mb concentration in the cell, the reported cellular diffusion coefficients, the PA dissociation constants from ligated Mb and FABP, a fatty acid flux model suggests that Mb can compete with FABP transporting cellular fatty acid.
General significance: Under oxygenated conditions and continuous energy demand, Mb dependent fatty acid transport could influence the cell's preference for carbohydrate or fatty acid as a fuel source and regulate fatty acid metabolism.

1. Introduction

Biochemistry textbooks have codified the function of Mb as an O_2 store or O_2 facilitated transporter. Yet, after half a century of research, questions still remain about Mb structure and function [29,72,73]. Certainly, experiments have demonstrated the importance of Mb in supplying O_2 in plants and in mammalian tissue. Indeed, in vivo NMR experiments have observed Mb releasing its O_2 store to sustain oxidative metabolism during apnea in seals and at the initiation of skeletal muscle contraction [11,52]. Yet the O_2 store of Mb can prolong respiration in a rat heart for only a few seconds during anoxia [10]. Upon CO inactivation of Mb function, the myocardium shows no compensating alteration in bioenergetics or contractile function response [9,20]. A mouse without Mb exhibits no striking impairments in its oxygen consumption rate, contractile function, bioenergetics, and metabolism [19,27]. Some researchers have now imputed a controversial NO bioscavenging and reductase function to Mb [18,35,37,57].

In the mouse model without Mb, myocardial metabolism switches its substrate preference from fatty acid to glucose. Fatty acid to glucose utilization ratio drops from 3/1 to 0.7/1 [17]. Given the conventional line of reasoning, the decline in oxidative fatty acid metabolism arises from a deficiency in Mb facilitated O_2 transport [17]. However, Mb appears to diffuse too slowly to compete effectively with free O_2 in normoxic heart [42,43,50,51]. Alternatively, the absence of Mb might indicate a diminished capacity to facilitate fatty acid transport. Indeed, early studies have suggested that Mb can bind fatty acid [25,26,28].

^{1}H NMR studies have recently interrogated the interaction of palmitate (PA) with Fe(III) MbCN and have found evidence for specific and non-specific binding [67]. Many studies use the paramagnetic Fe(III) MbCN as a structure–function model of the ligated physiological state of Mb, as represented by the diamagnetic Fe(II) MbO_2 or MbCO found in the cell, because the electron–nuclear interaction of the unpaired Fe(III) electron hyperfine shifts the heme and localized heme pocket amino acid residue signals into observable parts of the NMR spectral window [16]. The observation implies that PA also interacts with the physiological states of Mb.

Indeed, PA does interact specifically and non-specifically with MbCO, consistent with its interaction with MbCN. MbCO also increases PA solubility. However, PA does not appear to interact with deoxy Mb. The results suggest that ligated and unligated states of Mb exhibit distinct interactions with fatty acid and give rise to a modified view of intracellular

Abbreviations: PA, palmitate; FABP, fatty acid binding protein; Mb, myoglobin; MbCO, carbonmonoxy myoglobin

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fatty acid transport. Given the cellular Mb and fatty acid binding protein (FABP) diffusion coefficients, concentrations, and PA binding affinities, a fatty acid flux model indicates that ligated Mb can compete effectively with FABP to facilitate fatty acid transport [23,42,43]. Since deoxy Mb does not appear to interact with fatty acid, the differential interaction of ligated and unligated Mb suggests a convenient mechanism for fatty acid to load at the sarcolemma in the vicinity of a high PO_2 and unload the fatty acid and oxygen at the mitochondria in the environment of low PO_2. Mb can then follow the intracellular O_2 gradient from sarcolemma to the mitochondria to load and unload both fatty acid and oxygen without a need to invoke a complex explanation or mechanism as in the case with the high affinity FABP [71].

2. Materials and methods

2.1. Protein preparation

Myoglobin and albumin solutions were prepared from lyophilized horse heart protein and essentially fatty acid free bovine serum albumin (Sigma Chemical Inc., St. Louis, MO). Deoxy Mb was prepared from lyophilized metMb as described previously [36]. The preparation of MbCO solution followed a similar procedure. Dissolved oxygen from the metMb was removed and replaced with N_2. A 5 time excess of sodium dithionite was then injected to reduce the Fe(III) metMb to Fe(II) deoxy Mb and to remove any residual O_2. In the preparation of MbCO, the solution was equilibrated with CO. The resultant MbCO solution was loaded on a Sephadex G-25 column equilibrated with 30 mM Tris and 1 mM EDTA at pH 7.4. Elution with the same buffer removed the dithionite from the MbCO. Additional CO was then bubbled into the final MbCO solution. NMR tubes were sealed tightly with a rubber stopper.

2.2. Fatty acid-Mb preparation

Sodium palmitate (Sigma Chemical Inc., St. Louis, MO) was dissolved in 30 mM Tris buffer with 1 mM EDTA at pH 8.5 at 65 °C. Stock solutions of 10 mM and 100 mM were prepared and kept in a heating block (Thermolyne 17600 Dri-Bath) at 65 °C. An aliquot of 10 mM or 100 mM PA in Tris buffer at 65 °C was added to 600 μl of 0.2–0.8 mM myoglobin at 35 °C to yield a final solution with Mb:PA ratios from 1:0.1 to 1:4. All NMR experiments were then conducted at 35 °C. The time between PA addition and the start of the NMR measurement was approximately 5 min. The pH was measured at 35 °C using a calomel electrode (Orion 7110BN Micro Calomel pH, Thermo Electron Corporation).

2.3. NMR

Bruker Avance 500 and 600 MHz spectrometers measured the ^1H signals with a 5 mm probe. The ^1H 90° pulse, calibrated against the H_2O signal from a 0.15 M NaCl solution, was 9 μs. Watergate pulse sequence was used to obtain solvent suppression. Sodium-3-(trimethylsilyl) propionate 2,2,3,3 d4 (TSP) served as the internal chemical shift and concentration reference. All samples contained 5% D_2O to enable the deuterium lock during signal acquisition. All measurements were carried out at 35 °C. A typical spectrum required 1024 scans and used the following signal acquisition parameters: 12 kHz spectral width, 2560 data points, and 107 ms recycle time. Zero-filling the free induction decay (FID) and apodizing with an exponential window function improved the spectra. A spline fit then smoothed the baseline.

The ^{13}C signals collected at 151 MHz used the following acquisition parameters: 8.25 μs 90 pulse, a 33 kHz spectral window, and 16 K data point. A GARP pulse sequence decoupled the ^1H signals, and $^{13}C_2$ acetate provided an internal chemical shift reference at 24.2 ppm.

2.4. Intracellular fatty acid Transport

The intracellular fatty acid flux has contributions from free PA diffusion and protein mediated PA diffusion as expressed in the following equation, which approximates a zero free PA at the mitochondrial surface:

$$J = D_{PA}PA + D_X C_X \frac{PA}{K_D^X + PA} \quad (1)$$

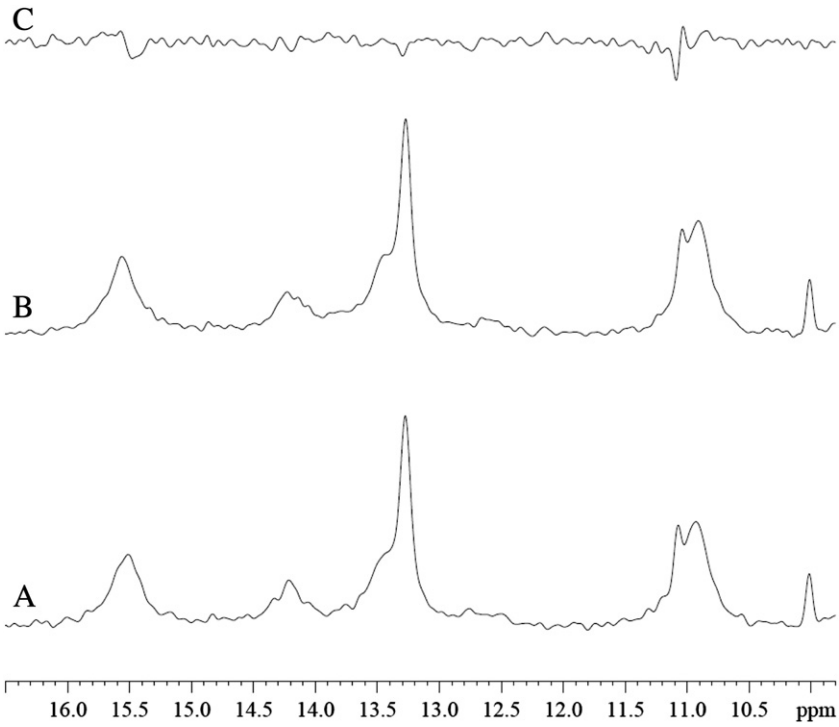

Fig. 1. ^1H NMR spectra of hyperfine shifted region of deoxy Mb Tris buffer at pH 7.4 at 35 °C: A. 0.8 mM deoxy Mb. B. 0.8 mM deoxy Mb and 3.2 mM PA. C. Difference of B − A.

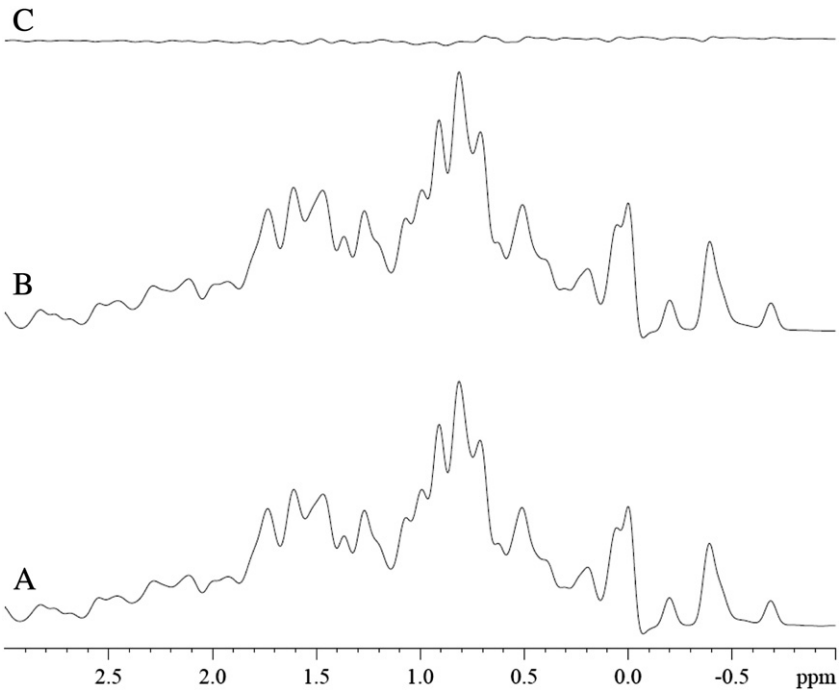

Fig. 2. ^{1}H NMR spectra of 0.8 mM deoxy Mb in Tris buffer at pH 7.4 at 35 °C. Spectra of: A. 0.8 mM deoxy Mb. B. 0.8 mM deoxy Mb and 3.2 mM PA. C. Difference of B–A.

J = the overall fatty acid flux, PA = soluble concentration of PA; C_X = cellular concentration of Mb or FABP; D_{PA} = diffusion coefficient of free PA, and D_X = diffusion coefficient of Mb or FABP in the cell, K_D^X = in vitro PA dissociation constant of Mb or FABP [42,43,45,59,67]. Because the reported D_{PA} in the cell varies widely from 3.5×10^{-9} cm^2 s^{-1} to 4.6×10^{-6} cm^2 s^{-1}, the model has used the highest value to set an upper bound for free acid contribution [45,68]. The model also assumes an identical in vitro and in vivo K_D^X.

2.5. Statistical analysis

Statistical analysis used the Sigma Plot/Sigma Stat program (Systat Software, Inc., Point Richmond, CA) and expressed the data as mean value ± standard error (SE). Nonlinear regression analysis of the average data points determined the dissociation constant using Marquardt–Levenberg algorithm. Statistical significance was determined by Student's *t*-test, $P < 0.05$.

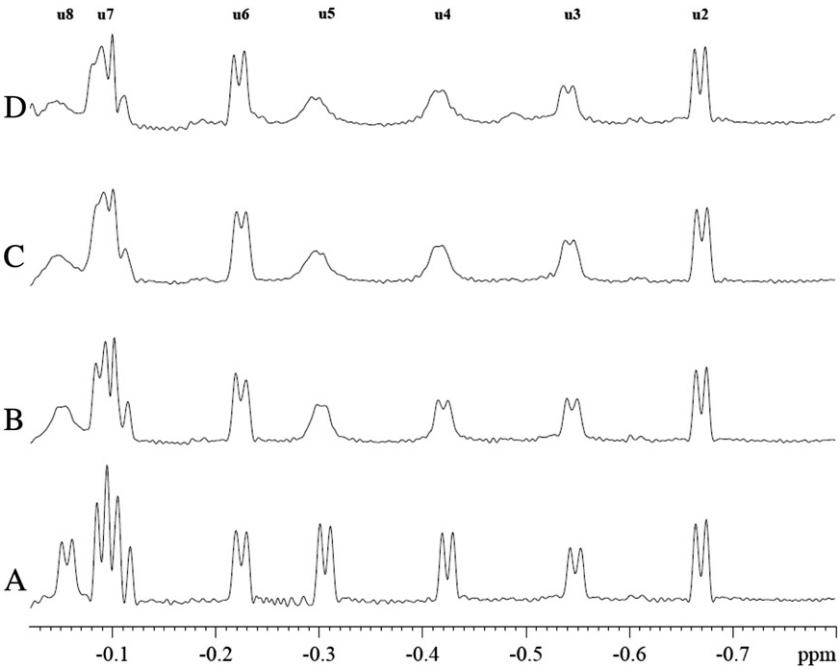

Fig. 3. PA perturbs specifically the ^{1}H NMR peaks (u3, u4, u5, u7, and u8) of MbCO in the spectral region from −0.05 to −0.8 ppm. PA has no effect on peaks u2, u6, and other peaks. The spectra show the signals from 0.8 mM MbCO with and without palmitate in 30 mM Tris and 1 mM EDTA at pH 7.4 and 35 °C. A. No PA. B. MbCO:PA = 1:0.1. C. MbCO:PA = 1:0.5.D. MbCO:PA = 1:1.

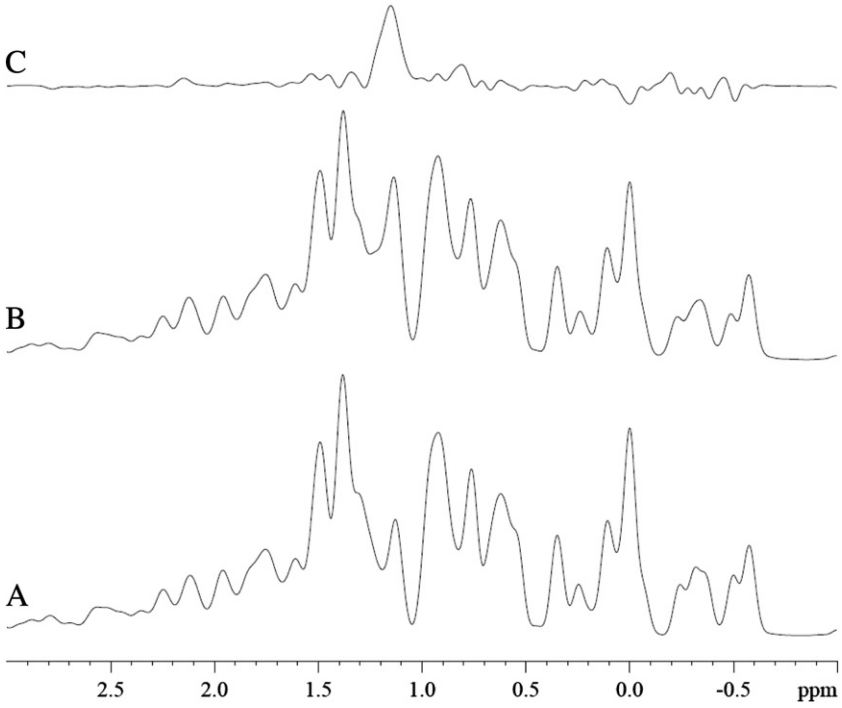

Fig. 4. ^{1}H NMR spectra of: A. MbCO. B. MbCO with 3.2 mM PA, and C. difference spectrum (B − A). The PA $-CH_2$ peak appears at 1.14 ppm, 0.15 ppm upfield from its 1.29 ppm chemical shift in Tris buffer at pH 7.4 and 35 °C [67].

3. Results

PA does not appear to interact with Fe(II) deoxy Mb. In the presence of PA, the hyperfine-shifted resonances of deoxy Mb exhibit no significant change in signal intensity or chemical shift, Fig. 1.

Moreover, no PA signal appears in the diamagnetic region of the deoxy Mb spectra, where the dominant PA $-CH_2$ signal would resonate. Fig. 2A shows the control spectrum of 0.8 mM deoxy Mb in 30 mM Tris buffer with 1 mM EDTA at pH of 7.4 at 35 °C. The addition of PA does not produce any detectable PA $-CH_2$ signal, Fig. 2B–C. Dithionite, a chemical required to produce deoxy Mb, does not alter either the PA $-CH_2$ signal intensity or chemical shift (data not shown).

In contrast, PA interacts specifically with MbCO. Fig. 3 shows the MbCO spectral response during a PA titration. The peaks (u3, u4, u5,

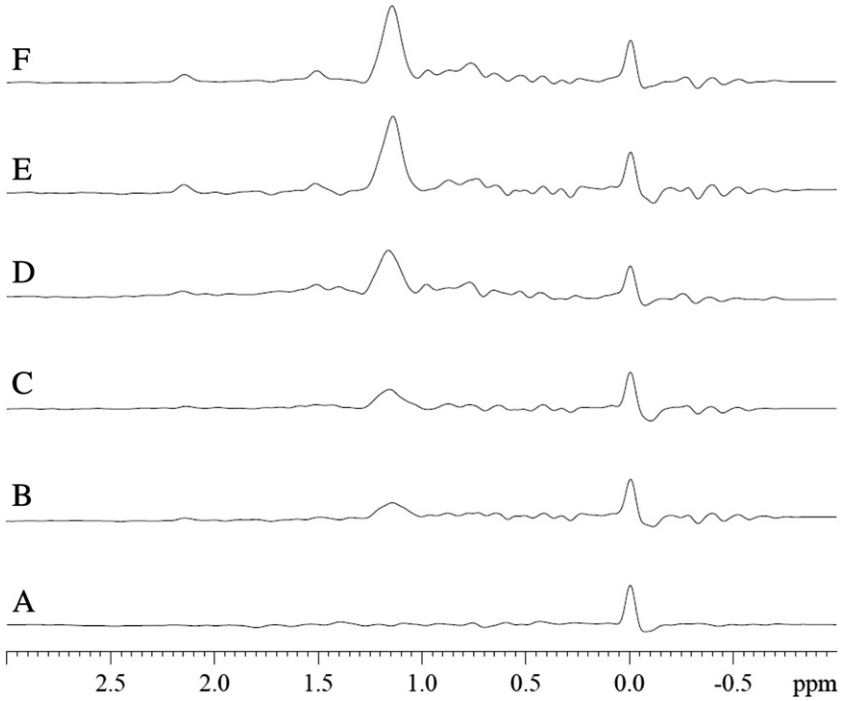

Fig. 5. ^{1}H NMR difference spectra of MbCO (MbCO with TSP and varying amount of PA –MbCO) in 30 mM Tris buffer and 1 mM EDTA at pH of 7.4 and 35 °C at MbCO :PA ratios: A. 1:0. B.1:0.5. C.1:1. D.1:2. E.1:3.5. F.1:4. The peak at 0 ppm corresponds to 3.2 mM TSP. The PA $-CH_2$ peak intensity increases as PA level increases.

u7, and u8) in the spectral region from −0.05 to −0.8 ppm decrease their signal intensity with the addition of PA. However, PA has no effect on peaks u2, u6, and other peaks. The most prominent change occurs with peaks u4 and u5.

^{1}H NMR also detects the $-CH_2$ PA peak in the presence of MbCO. Upon the addition of 3.2 mM of PA, the PA $-CH_2$ peak appears at 1.14 ppm, Fig. 4A–B. The difference spectrum reveals clearly the $-CH_2$ PA peak, Fig. 4C. The $-CH_2$ of PA in MbCO solution resonates 0.15 ppm upfield from its corresponding 1.29 ppm chemical shift position in Tris buffer at pH 7.4 and 35 °C [67].

Fig. 5 displays the ^{1}H difference spectra of MbCO with varying MbCO:PA ratios from 1:0 to 1:4. The peak at 0 ppm corresponds to 3.2 mM TSP internal reference. The PA $-CH_2$ peak intensity increases, as PA level increases.

In particular, the signal intensity of u4 and u5 decreases with increasing amount of PA. The signal intensity change reveals a PA dependence that reaches a saturating PA–Mb level and gives rise to an estimate of the apparent dissociation constants of 39 and 48 μM for u4 and u5, respectively, Fig. 6.

In Fig. 7, the graph reflects the non-specific interaction of PA with MbCO and MbCN, as determined by the area of the NMR visible $-CH_2$ PA signal. Up to 2.2 mM of the PA introduced into either MbCO or MbCN solution, only 41% appears as an NMR detectable signal. Above 2.2 mM, however, the soluble PA fraction no longer increases. Both MbCO and MbCN exhibit a similar non-specific PA interaction profile. The NMR visible PA fraction suggests a 0.8% solubility in Tris [67]. Table 1 tabulates the PA solubility in different Mb solution states.

The NMR spectra of $^{13}C_1$ PA in MbCO and deoxy Mb also confirm contrasting interactions. Upon the addition of $^{13}C_1$ PA in MbCO, the ^{13}C spectra show the PA carboxyl group signals appearing at both 173 and 182 ppm, Fig. 8A–B. In deoxy Mb, no $^{13}C_1$ PA signal appears, Fig. 8C–D. In Tris buffer at pH 7.4 and 9.5, $^{13}C_1$ PA produces signals at 172 and 184 ppm, respectively, Fig. 8E–F.

Bovine serum albumin (BSA) and Mb compete for PA. Fig. 9 displays the competitive binding of PA to BSA and Mb. Titrating PA into MbCO produces selective signal intensity changes, most notably in the decrease in peaks u4 and u5, Fig. 9A–B. However, with the addition of 0.8 mM bovine serum albumin (BSA), the peaks u4 and u5 recover to their initial intensity, Fig. 9C.

^{13}C experiments also detect the competitive binding of PA to MbCO and BSA, Fig. 10. Introducing $^{13}C_1$ PA in MbCO produces the distinct $^{13}C_1$ PA peak at 182 ppm, Fig. 10A–B. With the addition of BSA, the PA signal

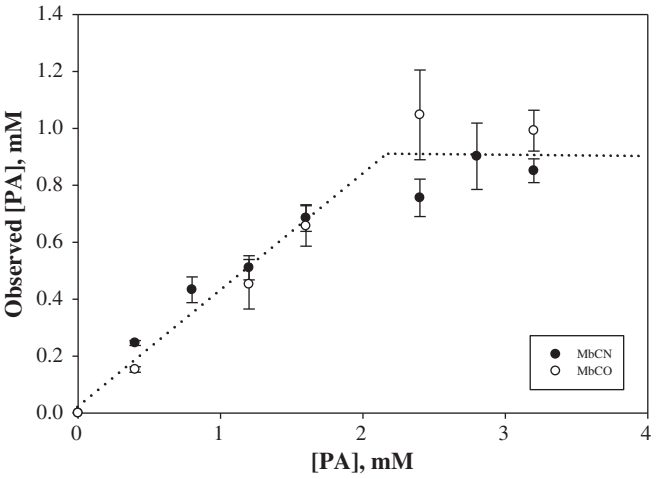

Fig. 7. Graph of the observed PA as a function of actual PA titrated into 0.8 mM MbCN and MbCO in Tris buffer at pH 7.4 at 35 °C. Below 2.2 mM added PA, the observed PA based on the concentration determined from the PA $-CH_2$ signal follows a linear relationship with a slope of 0.41. Above 2.2 mM, the observed PA remains constant at 0.91 mM. Both MbCO and MbCN exhibit a similar non-specific PA interaction profile. The NMR visible PA fraction suggests a solubility that exceeds the corresponding PA solubility in Tris buffer.

at 182 ppm disappears, and a new peak emerges at 184 ppm, corresponding to PA bound BSA.

The analysis of the $^{13}C_1$ PA signals during the titration of BSA into MbCO–PA reveals an apparent BSA/Mb partition coefficient of 16.5:1, Fig. 11. Using literature values for the dissociation constant (K_d) of PA bound to the first binding site in BSA (2–147 nM) and the apparent BSA/Mb partition coefficient leads to a corresponding apparent Mb–PA K_d of 0.03–2.4 μM [2,4,5,15,58,62,65,66].

The experimentally determined Mb–PA K_d provides input values to model the intracellular fatty acid flux, Table 2 and Eq. (1). Curve A in Fig. 12 models the free fatty acid flux based on PA solubility in Tris. Curve B estimates the FABP mediated fatty acid flux using a cellular FABP concentration of 50 μM, a K_d = 14 nM [21,60]. Curve C models the free fatty acid flux based on the enhanced solubility of PA in the presence of MbCO (41%). Curve D shows that MbCO facilitated transport of PA based on cellular concentration of [Mb] = 0.26 mM and the apparent K_d = 48 μM. A Mb–PA K_d = 48 μM would indicate a

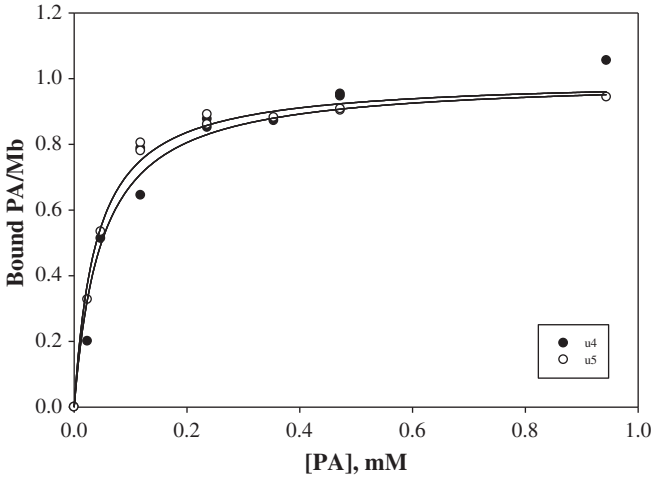

Fig. 6. The signal intensity graph of u4 and u5 during a PA titration reveals a concentration dependence that reaches a saturating PA–Mb level. The analysis of these curves yields apparent dissociation constants 39 and 48 μM for u4 and u5, respectively.

Table 1
Palmitate solubility in different solutions.

Solution	Solubility (M)	Solubility (g/100 g solvent)	Reference
0.8 mM MbCN in Tris, pH 7.4 35 °C	0.90×10^{-3}	2.50×10^{-2}	This work
0.8 mM MbCO in Tris, pH 7.4 35 °C	0.90×10^{-3}	2.50×10^{-2}	This work
0.8 mM deoxy Mb in Tris, pH 7.4 35 °C*	Not detectable	Not detectable	This work
Tris buffer pH 7.4 35 °C	3.16×10^{-6}	8.79×10^{-5}	[67]
0.2 mM MbCN in Tris, pH 7.4 35 °C	0.13×10^{-3}	3.62×10^{-3}	[67]
0.2 mM lysozyme in Tris, pH 7.4 35 °C	0	0	[67]
99.4% of ethanol at 30 °C	0.93	23.9	[55]
Acetone at 30 °C	0.61	15.6	[55]
Benzene at 30 °C	1.35	34.8	[55]
Glacial acetic acid at 30 °C	0.31	8.11	[55]
66 mM phosphate buffer, pH 7.4 at 37 °C	$<10^{-10}$	$<2.78 \times 10^{-9}$	[70]
Water 20 °C	6.00×10^{-7}	1.53×10^{-5}	[54]
Water, pH 5.7, 25 °C	2.68×10^{-6}	6.87×10^{-5}	[61]
Water 30 °C	3.2×10^{-5}	8.3×10^{-4}	[55]

* No detectable NMR signal of palmitate.

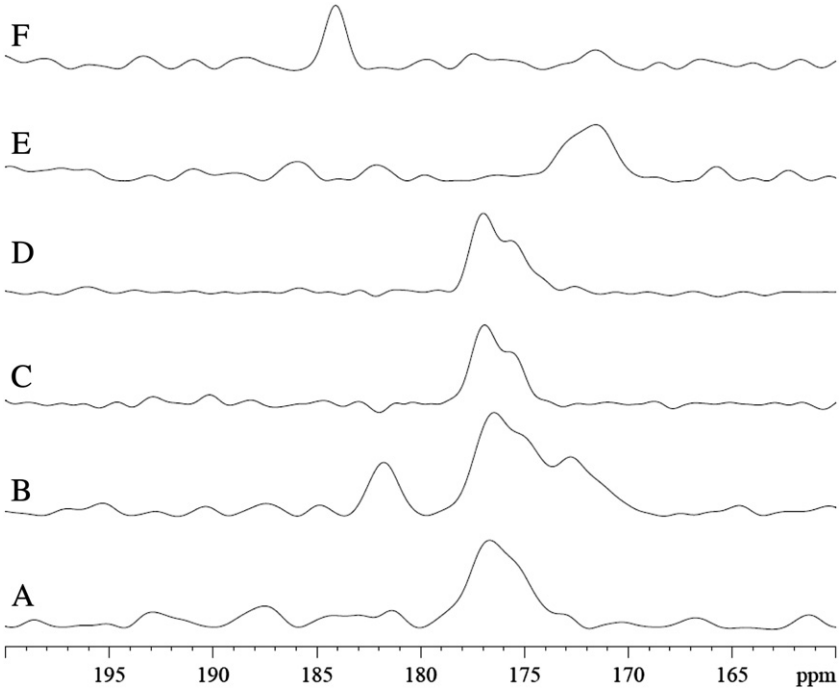

Fig. 8. $^{13}C_1$ PA in MbCO, deoxy Mb, and Tris exhibit contrasting spectra: A. 0.8 mM MbCO in 30 mM. Tris buffer at pH 7.4 at 35 °C.B. 0.8 mM MbCO with 0.8 mM PA. PA peaks appear at 173 and 182 ppm. C. 0.8 mM deoxy Mb. D. 0.8 mM deoxy Mb with 0.8 mM PA. E. 3.2 mM PA in Tris buffer, pH 7.4. $^{13}C_1$ PA appears at 172 ppm. F. 3.2 mM PA in Tris buffer, pH 9.5. $^{13}C_1$ PA appears at 184 ppm.

Mb facilitated PA flux exceeding the FABP facilitated PA flux at cellular PA concentration above 0.02 μM [48,67]. The V_{max} values per g tissue for FABP $= 1.5 \times 10^{-7}$ nmol cm^2 s^{-1} g^{-1} and for Mb $= 2.0 \times 10^{-4}$ nmol cm^2 s^{-1} g^{-1}. The model assumes that deoxy Mb does not bind PA and therefore cannot facilitate PA transport.

Fig. 13 models the fatty acid flux at high PA and Mb concentration. Curve A: FABP facilitated fatty acid flux. Curve B: fatty acid flux based on [Mb] = 0.26 mM and the apparent K_d = 48 μM. Curve D shows fatty acid flux based on [Mb] = 3.8 mM and the apparent K_d = 48 μM [48,52]. At high Mb concentration, Mb facilitated PA transport

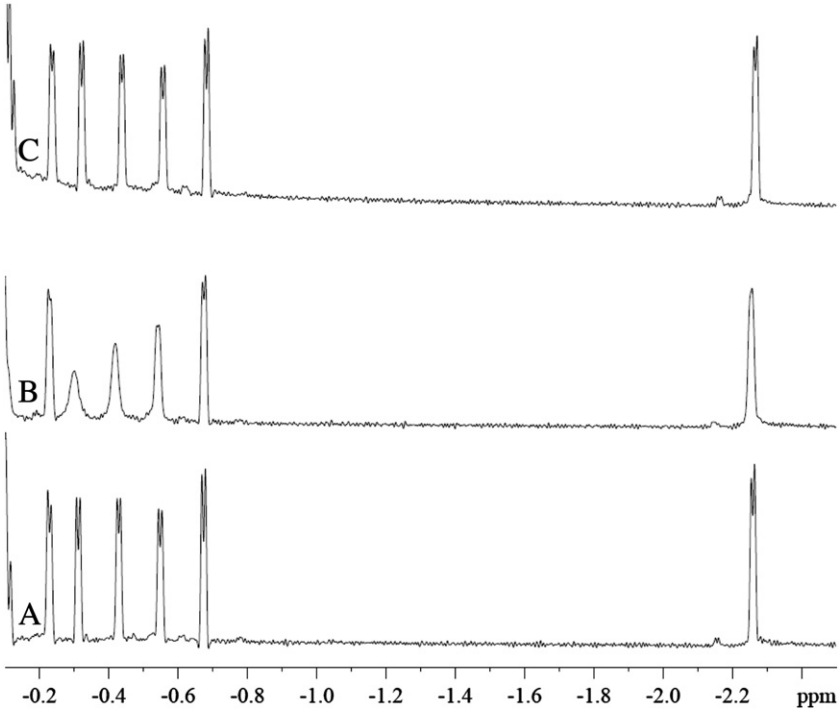

Fig. 9. Bovine serum albumin (BSA) and PA bound Mb. ^{1}H NMR spectra from: A. 0.8 mM MbCN. B. MbCN:PA 1:1. C. MbCN:PA:BSA 1:1:1. PA binding to Mb reduces selectively the intensity of peaks u4 and u5. Upon addition of BSA, these peaks return to their respective control levels.

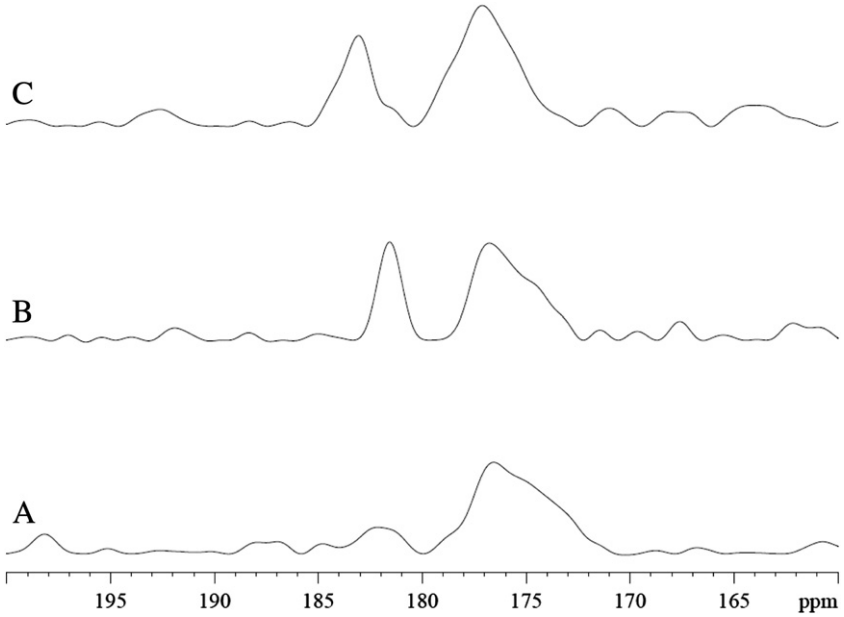

Fig. 10. Bovine serum albumin (BSA) and $^{13}C_1$ PA bound Mb. ^{13}C NMR spectra from: A. 0.8 mM MbCN. B. MbCN:$^{13}C_1$ PA 1:1. C. MbCN: $^{13}C_1$ PA:BSA 1:1:1. PA binding to Mb introduces a signal at 182 ppm. Upon addition of BSA, the signal shifts to 184 ppm. $^{13}C_1$ PA in BSA also shows a peak at 184 ppm (data not shown).

predominates under all conditions and will reach a V_{max} value of 3×10^{-3} nmol cm^2 s^{-1} g^{-1} for 3.8 mM Mb observed in marine mammals.

4. Discussion

4.1. Palmitate with MbCO

Previous experiments have shown that the addition of PA to Fe(III) MbCN perturbs selectively the hyperfine shifted 8 heme methyl signal [67]. The observation has led to the hypothesis that Mb can specifically bind fatty acid in localized protein regions. Even though Fe(III) MbCN has served as an analog of the ligated state of Mb, questions still remain about fatty acid interaction with the physiological Fe(II) Mb, which can bind and release O_2 and CO. Indeed, the addition of palmitate produces a selective signal intensity loss in the ^{1}H NMR spectra of ligated MbCO, consistent with a specific palmitate–protein interaction. Palmitate induces intensity changes in several ring current shifted peaks, most notably u4 and u5. Literature reports have assigned these peaks to Val 17 and Leu 2 [47].

Analysis of the palmitate–MbCO titration curve of u4 leads to the determination of an apparent K_d of 39–48 μM, consistent with the MbCN K_d of 12–43 μM [67]. The apparent K_d values also agree with previous studies on MbO_2, which shows a lower binding capacity for PA than albumin on a per mole basis [24]. An assay of the competitive binding of PA to Mb and bovine serum albumin (BSA) shows a BSA/Mb partition coefficient of 16.5. BSA competes more effectively for PA than Mb. However, the literature contains many reports of fatty acid binding to BSA with widely varying number of binding sites from 1 to 8 and K_d values ranging from 2 to 1,000,000 nM [2,4,5,15,58,62,65,66]. Even limiting the K_d values reported for the 1st binding site of BSA still yields a range from 2 to 147 nM. These BSA K_d values and the apparent BSA/Mb partition coefficient of 16.5 would still lead to a wide range of Mb K_d values between 0.03 and 2.4 μM, which unfortunately precludes a confident assessment of the Mb–PA binding affinity. Nevertheless, the analysis suggests that the NMR calculation overestimates the actual K_d value (vide infra).

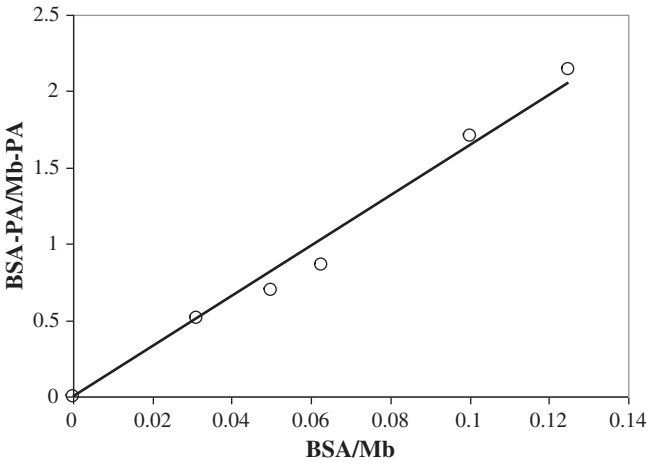

Fig. 11. Adding BSA to a 1:1 PA:Mb solution reveals a partition coefficient of 16.5 for the Mb vs. BSA PA affinity.

Table 2
Fatty acid flux model parameters.

Parameter		Value	Reference
Concentration, rat heart (μM)	FABP (C_{FABP})	50	[68]
	Myoglobin (C_{Mb})	260	[48]
Dissociation constant (μM)	K_{Mb}	48.3	This Work
	K_{FABP}	14.0×10^{-3}	[21,60].
Diffusion constant (D, cm^2 s^{-1})	Fatty acid (D_{FA})*	4.6×10^{-6}	[68]
	FABP (C_{FABP})	3.05×10^{-9}	[45]
	Myoglobin (C_{Mb})	7.85×10^{-7}	[43]
Equipoise [PA] at flux A = flux B (μM)	Mb & FABP	0.02	This work
	PA in Mb & FABP	0.07	This work
Maximum facilitated fatty acid flux (nmol cm^{2}s^{-1} g^{-1})	Mb in rat heart	2.0×10^{-4}	This work
	Mb in seal muscle	30.0×10^{-4}	This work
	FABP	1.5×10^{-7}	This work
PA solubility (M)**	Tris	3.16×10^{-6}	[67]
	MbCN	0.97×10^{-3}	This work
	MbCO	0.97×10^{-3}	This work
	Deoxy Mb	Not detectable	This work

* The reported fatty diffusion coefficient, D_{FA}, varies widely. The fatty flux model has used the fastest reported diffusion coefficient of 4.6×10^{-6} cm^2/s to set an upper bound contribution for free FA flux.

** Solubility estimated from the observed ^{1}H NMR visible $-CH_2$ signal of palmitate in a 0.4 mM Mb solution.

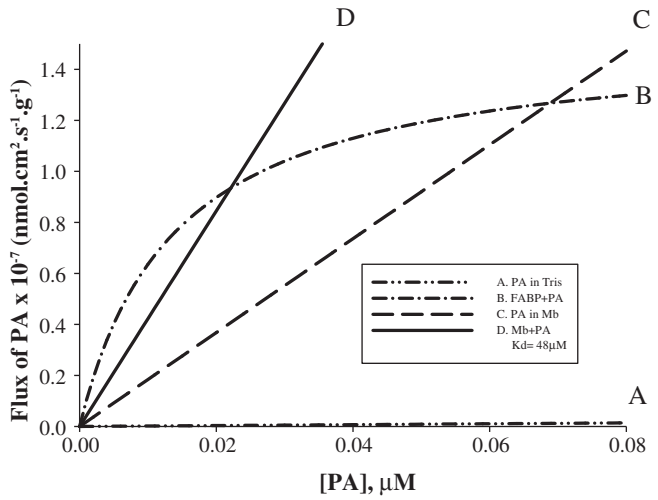

Fig. 12. Model of palmitate flux at low palmitate concentration: A. PA in Tris (0.8% solubility). B. FABP facilitated transport of fatty acid (50 μM FABP, Kd = 14 nM). C. PA in the presence of Mb (41% solubility). D. Mb facilitated transport of PA (Mb = 0.26 mM, Kd = 48 μM). PA flux in the presence of Mb exceeds FABP facilitated PA flux above 0.07 μM PA. Mb mediated transport of PA exceeds FABP–PA flux at PA concentration above 0.02 μM PA. The Vmax values per g tissue for FABP = 1.5×10^{-7} nmol cm^2 s^{-1} g^{-1} and for Mb = 2.0×10^{-4} nmol cm^2 s^{-1} g^{-1}. The corresponding 1/2 Vmax for FABP = 7.5×10^{-8} nmol cm^2 s^{-1} g^{-1} and for Mb = 1.0×10^{-4} nmol cm^2 s^{-1} g^{-1}.

4.2. Palmitate with deoxy Mb

In contrast, unligated Fe(II) Mb (deoxygenated Mb) shows no detectable interaction with PA. PA does not perturb any detectable signals from the heme $5CH_3$, 6Hα propionate, 4Hα vinyl, 2Hα vinyl, and 7Hα propionate, as observed in the hyperfine shifted 10–15 ppm spectral region [6,39]. No hyperfine shifted signals in the upfield region appear perturbed. Given the postulated interaction of fatty acid near the 8 heme methyl, the adjacent 7Hα propionate group should experience a significant structural perturbation and exhibit spectral alteration. PA does not perturb the NMR observable 7Hα propionate peak at 11 ppm. The observation stands in sharp contrast to the detectable PA interaction with MbCN and MbCO.

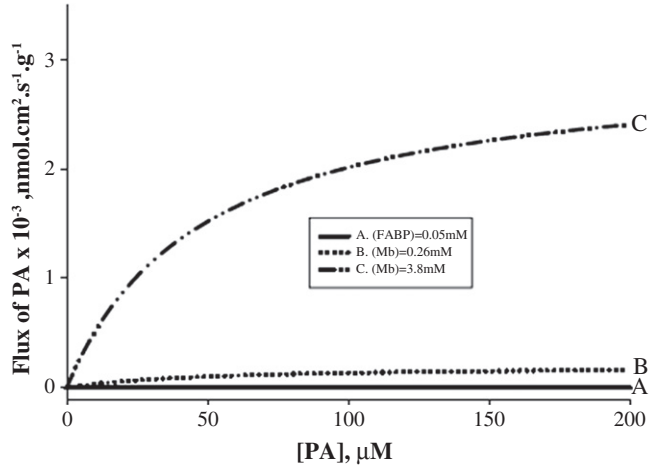

Fig. 13. Model of fatty acid flux at high palmitate concentration: A. FABP facilitated transport of fatty acid (50 μM FABP, Kd = 14 nM). B. Mb facilitated transport of PA (Mb = 0.26 mM, Kd = 48 μM). C. Mb facilitated transport of PA (Mb = 3.8 mM, Kd = 48 μM). The Vmax values per g tissue for Mb facilitated fatty acid transport in rat heart = 2.0×10^{-4} nmol cm^2 s^{-1} g^{-1} and in seal muscle = 30×10^{-4} nmol cm^2 s^{-1} g^{-1}.

4.3. Non-specific interaction of palmitate with MbCO and deoxy Mb

In addition to the specific interaction, PA interacts non-specifically with MbCO. The non-specific interaction leads to a detectable increase in the PA methylene peak signal, which reflects about a 10^4 times higher PA solubility in the presence of MbCN than in buffer [67]. Associated with a non-specific interaction, the methylene signal of PA in MbCN shifts upfield by 0.15 ppm from its corresponding position observed in buffer [12].

The titration of PA into MbCO induces also a 0.15 ppm upfield shift of the methylene ($-CH_2$) groups of PA. PA in MbCN vs. MbCO yields a comparable $-CH_2$ PA signal intensity. In contrast, deoxy Mb does not exhibit any non-specific interaction with PA and does not enhance the PA solubility at wide range of Mb:PA ratios. Upon adding dithionite to the MbCN–PA solution, deoxy Mb forms immediately. The methylene signal of PA disappears, consistent with a loss of non-specific interaction of PA with Mb. Adding dithionite to the buffer solution containing PA also does not alter the PA $-CH_2$ signal intensity nor chemical shift at 1.29 ppm. Dithionite has no effect on either the PA chemical shift or solubility.

4.4. Comparison of interaction with MbCN and MbCO

In many protein structure studies, Fe(III) MbCN has served as a surrogate model of the ligated form of the physiological Fe(II) MbO_2 or MbCO, because the electron–nuclear interaction of the paramagnetic Fe(III) shifts by hyperfine interaction the heme and localized heme pocket amino acid residue signals into observable parts of the NMR spectral window [38]. These signals permit then a sensitive tracking of the interaction between the heme electronic and protein structures. In contrast, detecting the corresponding heme signals in MbO_2 or MbCO poses a technical challenge, since these peaks resonate in a crowded, overlapping spectral region of the diamagnetic Fe(II) protein. Specifically, the heme methyl signals of both MbCO and MbO_2 appear within a diamagnetic region around 3.5 ppm. In particular, the 8 heme methyl signal resonates at 3.59 ppm [6,46].

Because MbCO and MbCN share key structural features, they should exhibit similar specific and non-specific interactions. Indeed, the PA does interact specifically with MbCO and MbCN and shows the same increased PA solubility, which stands well above PA solubility in buffer [67]. Moreover, in the presence of either MbCO or MbCN, the PA $-CH_2$ peak shifts from 1.29 ppm (chemical shift observed in buffer) to 1.14 ppm. Up to 2.2 mM added PA, the soluble PA fraction in MbCO or MbCN increases linearly with a slope of 0.41. Above 2.2 mM added PA, the soluble PA fraction appears to plateau at 9×10^{-4} M. The maximum solubility appears higher than previously reported for PA in MbCN and arises most likely from a switch in the experiment method, which uses glass rather than plastic pipettes to transfer fatty acid during PA titration [67]. The literature has reported a PA solubility of 3.2×10^{-6} M in water at 30 °C and $<3.2 \times 10^{-6}$ M in pH 7.4 phosphate buffer at 37 °C, Table 1.

4.5. ^{13}C NMR of PA in Mb

In titrating $^{13}C_1$ PA into Mb solution, two peaks appear immediately in the ^{13}C spectra. The dominant one resonates at 182 ppm, while the broad smaller peak appears at 173 ppm. The 182 ppm signal increases with PA addition well beyond the 1:1 stoichiometric ratio of PA:Mb and appears consistent with a non-specific binding rather than a specific binding of PA to Mb. Comparing the ^{13}C spectra of $^{13}C_1$ PA in buffer at pH 7.4 and 9.5, where the lamellar and micellar form of fatty acid exhibits a $^{13}C_1$ PA signal at 172 ppm and 184 ppm, respectively, suggests that Mb appears to shift the equilibrium between the lamellar and micellar forms of PA toward the micellar form.

4.6. Structural interaction of Mb with fatty acid

The crystallographic view of a closely packed Mb structure seems to preclude any fatty acid binding. However, Mb does exhibit transient fluctuations that open distinct pathways for ligands to migrate from its surrounding to the heme [14]. Specifically, researchers have postulated a specific role for the 6 and 7 heme propionates. Near the heme 6 propionate, Lys 45 (horse Mb) or Arg 45 (sperm whale Mb) regulates purportedly ligand migration from the protein surface to heme [7,40,41]. In sperm whale MbCN, Arg 45 forms hydrogen bonds with the carboxylate of Asp E3 and the 6-propionate. In horse Mb, the short side chain of Lys 45 cannot form hydrogen bonds with both carboxylates. Without the hydrogen bonds, the 6-propionate of horse Mb exhibits a greater mobility than the corresponding propionate of sperm whale Mb, and associated protein region displays less structural features. This enhanced flexibility in the ligated state of Mb has helped to rationalize the difference in ligand K_{on} and K_{off} for horse Mb and sperm whale Mb. In contrast, the 7 propionate remains mobile in both ligated sperm whale and horse Mb, since it has a similar molecular stabilization configuration.

In deoxy Mb, 2D NMR measurements have detected that the 7 propionate exhibits a greater mobility than the 6 propionate group, as reflected by the nuclear Overhauser enhancements (NOEs) from the propionates to the respective 5 and 8 heme methyls [6]. The propionate mobility in different ligation states of Mb influences ligand migration and may also modulate the selective binding of fatty acid [40,41,56]. In the MbCN spectrum, only the 8-heme methyl neighboring the 7-propionate experiences a signal perturbation upon the addition of PA. In the deoxy Mb spectrum, no hyperfine shifted peak exhibits any perturbation.

The PA molecule appears to interact with other regions of Mb, as reflected in the perturbation of the upfield resonances in the MbCO spectra. Neither amino acid residue Val 17 nor Leu 2 (peaks u4 and u5) neighbors the heme 8-methyl group. What gives rise to the contrasting PA interaction requires further investigation.

4.7. Implication for Mb and intracellular fatty acid transport

Because the cell contains organelles, proteins, and other macromolecules, the fatty acid solubility in buffer may not accurately reflect the actual solubility in the cell. In fact, proteins will most likely have a range of non-specific interactions. A previous study has shown, for example, that lysozyme has no interaction with fatty acid [67].

The contrasting PA interactions with MbCO and deoxy Mb suggest a potential role for Mb in regulating directly fatty acid metabolism. Current model ascribes an exclusive function to FABP as a carrier of intracellular fatty acid. Rat heart contains about 50 μM of FABP with a K_d of 14 nM for fatty acid [21,60]. Despite FABP's high affinity for fatty acid, many unresolved questions still surround the hypothesis that FABP alone facilitates fatty acid transport in the cell [22,44,69,71,75].

At low fatty acid concentration, the high affinity FABP will first bind fatty acid. Fatty acid flux, however, does not depend only upon binding affinity. It also depends upon protein concentration and diffusivity. Rodent heart contains 5 times more Mb (260 μM) than FABP (50 μM) [48,67].

For FABP, the literature has reported a diffusion coefficient in the cell of $3.05\times10^{-9}\,cm^2\,s^{-1}$ and a Kd of 14 nM. Consequently, FABP can facilitate fatty acid flux at a maximal rate of $1.5\times10^{-7}\,nmol\,cm^2\,s^{-1}\,g^{-1}$[45]. Cellular Mb, however, diffuses at $7.85\times10^{-7}\,cm^2\,s^{-1}$. Using the apparent Kd of 48 μM for PA binding to MbCO as the dissociation constant for ligated state of Mb, Mb facilitated fatty acid flux will reach a much higher flux rate of 2.0×10^{-4} nmol cm^2 s^{-1} g^{-1} in rat heart and $30\times10^{-4}\,nmol\,cm^2\,s^{-1}\,g^{-1}$ in seal skeletal muscle. Seal muscle contains about 15 times more myoglobin than rodent muscle.

Because all PA does not necessarily dissolve in the Mb solution, the apparent K_d calculation most likely overestimates the actual value. The BSA–PA partition coefficient analysis also suggests a lower K_d. A lower K_d implies that Mb will exceed FABP in transporting fatty acid at a lower cellular fatty acid concentration. Future studies using other approaches, such as fluorometric and isothermal calorimetry techniques, will provide additional clarification of the K_d value. Regardless of the K_d, however, Mb appears to have a much higher capacity to transport fatty acid in the cell.

4.8. A model of intracellular fatty acid transport

In principle, the intracellular fatty acid flux has contributions from carrier mediated transport and free diffusion. Because PA solubility increases appreciably in the presence of Mb, the free fatty acid would contribute much more than its solubility in buffer might suggest. In buffer, the low solubility would appear to militate against any significant contribution of free fatty acid. In Mb solution, however, PA solubility increases dramatically.

Moreover, because MbCN and MbCO interact non-specifically with PA in a similar way, it suggests that MbO_2 can influence the available fatty acid pool and the capacity to transport PA in the cell. In contrast, when Mb becomes deoxygenated, its capacity to interact with fatty acid diminishes. As a consequence, fatty acid availability would have a dependence on cellular partial pressure of oxygen (PO_2), especially along a PO_2 gradient from the sarcolemma near the capillary to the mitochondria, where fatty oxidation occurs and where cytochrome oxidase operates at a purported Km of about 0.1 mm Hg of PO_2 [37,74]. The contrasting O_2 dependent Mb affinity for fatty acid presents a convenient mechanism to load and unload fatty acid at different cellular sites, depending upon the PO_2 environment and the Mb oxygenation state.

Imputing a fatty acid transport role for Mb agrees with previous observations, which found ^{14}C labeled oleic acid binding to a rat heart cytosolic fraction of 16 kD molecular weight, which includes both Mb and FABP [26,63]. Because Mb has an approximately 3000 times lower binding affinity than FABP and a lower binding affinity than albumin, the role of Mb as a fatty acid transport might appear surprising. However, the high fatty acid affinity for FABP in the current model of intracellular fatty acid transporter requires potentially a complex mechanism to release fatty acid at the metabolism site [13]. In contrast, the high Mb concentration relative to the low FABP concentration and the Mb fatty acid affinity shifting with respect to PO_2 might enable Mb to compete effectively with FABP to transport fatty acid transport [24,67].

Given the proposed model of Mb facilitated fatty acid transport, FABP would initially bind PA in the cell and serve as the major transporter below 0.02 μM PA. In all cases, the V_{max} per g tissue for FABP ($1.5\times10^{-7}\,nmol\,cm^2\,s^{-1}\,g^{-1}$) falls far below the corresponding Vmax for Mb (2.0×10^{-4} nmol cm^2 s^{-1} g^{-1}). The contrasting Vmax values arise in part from the higher concentration of Mb (260 μM) over FABP (50 μM).

Indeed, Mb dependent transport of lipid would certainly broaden the cell's ability to meet a range of metabolic demands for fatty acid and would suggest an alternative explanation of how exercise induced increase in Mb concentration could potentially modulate metabolism [1,64].

4.9. Physiological implication of Mb facilitated fatty acid transport

The Mb facilitated flux of fatty acid would significantly impact cellular bioenergetics during a continuous demand for fatty acid oxidation, especially with respect to trained and untrained muscle. Energy generation relies more on lipid than carbohydrate below the crossover point of about 70% whole body maximum rate of oxygen consumption (VO_{2max}) and during postexercise recovery [3]. Training shifts the crossover point to a higher relative VO_{2max}. Most researchers ascribe the capacity to utilize fatty acid at a higher relative VO_{2max} or exercise intensity to an increase in mitochondrial mass, which would support increased fatty acid oxidation [31–33,49]. Training, however, also appears to increase

the Mb concentration, which conventional analysis would view as an increased O_2 transport capacity [1,30]. Since neither in vivo NMR nor fluorometric experiments have observed convincing data to show that Mb diffusion can compete effectively with free O_2, Mb dependent fatty acid transport might offer an alternative explanation of how Mb can expand fatty acid utilization in trained muscle [42,43,50,51].

Even at the beginning of muscle contraction, fatty acid bound to Mb might play a significant role. ^{1}H NMR studies have noted a rapid desaturation of Mb at the initiation of contraction, and the analysis of the kinetics indicates a sudden rise in intracellular oxygen consumption [11]. A rapid formation of deoxy Mb from MbO_2 would also imply a quick release of fatty acid to fuel ATP formation. A sudden surge in fatty acid utilization at the initiation of contraction, however, seems odd given the common notion that carbohydrate metabolism proceeds much faster than fatty acid metabolism.

For marine mammals, the Mb concentration in skeletal muscle can rise to 3.8 mM. Mb dependent fatty acid flux probably dominates under all physiological conditions [52,53]. In rodent heart, Mb reaches only 0.26 mM and can support only a fatty acid flux of 2.04×10^{-4} nmol cm^2 s^{-1} g^{-1} [48]. In contrast, Mb dependent fatty acid flux in the skeletal muscle of seal can rise to 30×10^{-4} nmol cm^2 s^{-1} g^{-1}.

Mb dependent fatty acid transport may have a unique role in diving mammals. In contrast to common misconception, seals holding their breath during a prolonged dive do not exhibit any sign of anaerobiosis, as indicated by significant lactate washout in the blood [8]. They still rely on oxidative fatty acid metabolism. In eupnea–apnea cycle studies of elephant seals (*Mirounga angustirostris*), a model of diving physiology, the blood does supply during eupnea an adequate amount of O_2 to saturate at least 90% of the cellular MbO_2 [53]. During apnea, the seal spontaneously holds its breath between 8 and 12 min, and the muscle releases its Mb oxygen store. But the intracellular O_2 level falls only modestly and still saturates Mb at 80%. A reduced cellular O_2 level doesn't necessarily presage anaerobic metabolism, consistent with recent discussion on the bioenergetics of muscle contraction [11,34]. Indeed during the breath hold in apnea, the cell still remains sufficiently aerobic. PCr and ATP stay at a constant level. PH doesn't change. Lactate formation does not increase. During a breath hold, seal muscle still maintains a highly saturated MbO_2, which can still support fatty transport for oxidative metabolism.

Nevertheless, how Mb contributes to the cell's fuel source selection, as suggested by the findings in this report, remains an open question that requires further investigation.

5. Conclusions

The ^{1}H NMR analysis reveals that PA interacts specifically and non-specifically with MbCO. It does not interact with deoxy Mb. Given the diffusion coefficient in the cell, cellular concentration, and the assumption of an identical K_d for MbO_2 as for MbCO, a model of intracellular fatty acid transport indicates that Mb mediated fatty acid diffusion could contribute significantly. Moreover, the differential PA interaction with Mb with respect to PO_2 suggests a convenient mechanism to load and unload PA.

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