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Choice of oils for essential fat supplements can enhance production of abnormal metabolites in fat oxidation disorders

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Abstract

Patients with mitochondrial long-chain fat oxidation deficiencies are usually treated with diets containing reduced fat and increased carbohydrate, at times via gastrostomy feeding. To ensure adequate intake of essential fatty acids, supplements are provided to their diets using commercially available oils. These oils contain large quantities of non-essential fats that are preferentially oxidized and produce disease-specific metabolites (acyl-CoA intermediates) due to the genetic defect. This study describes the concentrations of these intermediates as reflected by acylcarnitines as well as the % contribution from each of four fatty acids: palmitate, oleate, linoleate, and α -linolenate when incubated with fibroblasts from patients with VLCAD, LCHAD, and trifunctional protein (TFP) deficiencies. Palmitate and oleate produce the majority of disease-specific acylcarnitines with these defective cell lines (79–94%) whereas linoleate and linolenate produced less (6–21%). On average, the amount of acylcarnitines decreased with increasing unsaturation (C18:1 > C18:2 > C18:3:34% > 11% > 3%, respectively). This relationship may reflect the “gatekeeper” role of carnitine palmitoyltransferase I (CPT I). A diet comparison between Canola and a combination of Flax/Walnut oils revealed that the latter, containing the least amount of non-essential fats, reduced blood acylcarnitine levels by 33–36%. The etiology of the severe peripheral neuropathy of TFP deficiency may result from the unique metabolite, 3-keto-acyl-CoA, after conversion to a methylketone via spontaneous decarboxylation. Essential fatty acid supplementation with oils should consider these findings to decrease production of disease-specific acyl-CoA intermediates. © 2007 Elsevier Inc. All rights reserved.

Keywords: Fatty acid oxidation disorders; Diet supplements; Essential fats; Methylketones

Patients affected with mitochondrial long-chain fat oxidation disorders such as the very long-chain acyl-CoA dehydrogenase (VLCAD), trifunctional protein (TFP), and L-3-hydroxy-acyl-CoA dehydrogenase (LCHAD) deficiencies all require diets with reduced fat and increased carbohydrate composition sometimes involving gastrostomy feedings. The necessary reduction in dietary fat often requires an additional source of the essential fats, linoleate (C18:2) and α -linolenate (C18:3). These are essential since they are required for synthesis of important compounds such as docosahexenoate (DHA), prostaglandins, thromboxanes, etc. [1]. To provide the essential fatty acids, diets

are supplemented with commercially available oils [2]. Each of these contain substantial amounts of non-essential fats such as palmitate (C16), stearate (C18:0), and oleate (C18:1). These fatty acids are non-essential since they can be endogenously synthesized and are not involved in the synthesis of the important lipids mentioned above. However, they do enter β -oxidation and contribute substantially, to the accumulation of the abnormal acyl-CoA intermediates observed as acylcarnitines in the long-chain fat oxidation disorders.

This study examines the relative contributions of these essential and non-essential fatty acids to the accumulation of abnormal metabolites, in defective fibroblasts. Then, two patients received diets of either canola or a combination of Flax and Walnut oils to observe the impact on blood acylcarnitine levels.

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53 Materials and methods

54 Media and reagents

55 All tissue culture reagents and media were obtained from Gibco/BRL
56 (Gaithersburg, MD) or Atlanta Biologicals (Norcross, GA). Dulbecco's
57 Modified Eagle Medium (DMEM), 1X, low glucose (25 mM), with L-glu-
58 tamine (4 mM) was used as the basic growth media. L-Carnitine and fatty
59 acid precursors were purchased from Sigma Chemical (St. Louis, MO). All
60 other chemicals were of analytical grade.

61 Fibroblast cell lines

62 These were obtained from four patients with specific fat oxidation dis-
63 orders: VLCAD (1), TFP (1), and LCHAD (2). Diagnosis was confirmed
64 on each by performing the established "in vitro probe" technique using
65 $16\text{-}^2\text{H}_3$ -palmitic acid in intact fibroblasts and direct enzyme assay.

66 Patient diet comparisons

67 Two patients (VLCAD and TFP deficient), both receiving tube feed-
68 ings containing provimin, polycose, and triheptanoin (C7), agreed to diet
69 modifications of essential fatty acid supplements. The TFP patient's diet
70 with Canola oil supplement contained protein 14%, carbohydrate 30%,
71 fat (canola oil) 21%, and C7 35%. Linoleate and linolenate were 3% and
72 1.3% of total Kcal, respectively. After 3 days of the Canola supplemented
73 diet, the fat was changed to Flax/Walnut providing linoleate and linole-
74 nate at 3.1% and 1.6% of total Kcal, respectively. The VLCAD patient's
75 initial diet consisted of protein 14%, carbohydrate 30%, fat (canola)
76 15%, and C7 39%. Linoleate and linolenate were 3% and 1.4% of total
77 Kcal, respectively. The Flax/Walnut supplemented diet provided linoleate
78 and linolenate at 3.0% and 1.4% of total Kcal, respectively. Blood for
79 acylcarnitine analysis was obtained on the third day of the Canola diet
80 and again 3 days after changing to the Flax/Walnut diet.

81 All studies were approved by the Baylor University Medical Center
82 Institutional Review Board.

83 Enzyme activity

84 Activity was measured in cultured skin fibroblasts using established
85 methods previously described for VLCAD [3], LCHAD [4], and TFP [5].

86 Fibroblast cultures

87 Fibroblasts from all patients and controls were maintained in complete
88 DMEM at 37 °C in a humidified 5% CO₂/95% air incubator. Approx-
89 imately 1–3 days before initiation of incubation studies, the cells were
90 sub-cultured into duplicate T-25 flasks and grown to within 90–95% con-
91 fluency (approx 0.15–0.40 mg protein).

92 Protein measurement

93 Protein concentration was determined by a modification of the Brad-
94 ford method [6] using the Bio-Rad protein assay (Bio-Rad, Hercules,
95 CA) with BSA as standard.

Incubation studies

97 Fibroblast cell lines from patients with suspected or proven VLCAD,
98 TFP, LCHAD deficiencies and control cell lines were incubated for 72 h
99 with 3.5 ml complete DMEM containing 0.4 mM L-carnitine plus the
100 0.2 mM of the fatty acid—palmitate (C16), oleate (C18:1), linoleate
101 (C18:2), and linolenate (C18:3)—bound to fatty acid free bovine serum
102 albumin (BSA) as previously described [7]. In simultaneous experiments,
103 the deficient and control cell lines were incubated *without* the labeled fatty
104 acids in 3.5 ml complete DMEM containing 0.4 mM L-carnitine in BSA to
105 serve as blank levels for the resulting acylcarnitine metabolites.

Sample preparation and acylcarnitine analysis

106 Cells were incubated for 72 h at 37 °C in humidified 5% CO₂/95% air.
107 After the incubation period, media and cells were collected and the acyl-
108 carnitines from 67 μl media and 33 μl cell homogenate were extracted
109 and derivitized in 100 μl of 3 N HCl in *n*-butanol (Regis, Morton, Grove,
110 IL) and analyzed as butylesters on a QUATTRO II tandem mass spec-
111 trometer (Waters Micromass, Beverly, MA) equipped with electrospray
112 ionization using a precursor scan of *m/z* 85 [8]. All acylcarnitines were
113 quantified; however, only the following were found to be elevated and per-
114 tinent to this study: from palmitate incubations: C16, C14, C12, 3-OH-
115 C16, 3-OH-C14, and 3-OH-C12; from oleate incubations: C18:1, C16:1,
116 C14:1, 3-OH-C18:1, 3-OH-C16:1, and 3-OH-C14:1; from linoleate incu-
117 bations: C18:2, C16:2, C14:2, 3-OH-C18:2, 3-OH-C16:2, and 3-OH-
118 C14:2; from α-linolenate incubations: C18:3, C16:3, C14:3, 3-OH-C18:3,
119 3-OH-C16:3, and 3-OH-C14:3.

120 The above acylcarnitines were expressed in nanomoles per mg protein
121 per 72 h after subtracting "blank" levels determined in cultures without a
122 precursor fatty acid. Statistical analysis of this data included the mean and
123 standard deviation as well as *t*-test.
124

Results

125 The fatty acid composition in 100 g of five commercially
126 available oils was obtained from the USDA Nutrient Data-
127 base [9] (Table 1). The non-essential fats, palmitate, stea-
128 rate, and oleate, account for 31.0–67.7% of the fatty acid
129 composition of these oils with the largest amount found
130 in Canola oil. Conversely, the essential fats, linoleate and
131 α-linolenate, ranged from a low level of 32.3% in Canola
132 to the highest concentrations in Walnut and Flaxseed oil
133 (67.0–69.0%, respectively).
134

135 Cell lines from normal and four patients with VLCAD
136 (1), TFP (1), and LCHAD (2) were studied in vitro. The
137 results of the enzyme assays (nmol/min/mg protein) docu-
138 menting the deficiencies from the four defective cell lines
139 were as follows: *VLCAD*: 0.02 (mean 1.57; range: 1.26–
140 1.88); *TFP*: LCHAD: 19.6 (mean 89.9; range 74.3–105.5);
141 Thiolase: 0.9 (mean 28.7; range 23.3–34.1); *LCHAD-1*:
142 LCHAD: 18.8 (mean 89.9; range 74.3–105.5); *LCHAD-2*:

Table 1
Comparison of fatty acid composition of commercial oils (g/100 g oil)

Oils	C16 + C18	C18:1	C18:2	C18:3	Non-essential	Essential
Canola	5.8	56.1	20.3	9.3	61.9	29.6
Soy	14.1	22.8	51.0	6.8	36.9	57.8
Corn	12.4	27.3	53.5	1.2	39.7	40.9
Flaxseed	9.4	20.2	12.7	53.3	29.6	66.0
Walnut	9.0	22.2	52.9	10.4	31.2	63.3

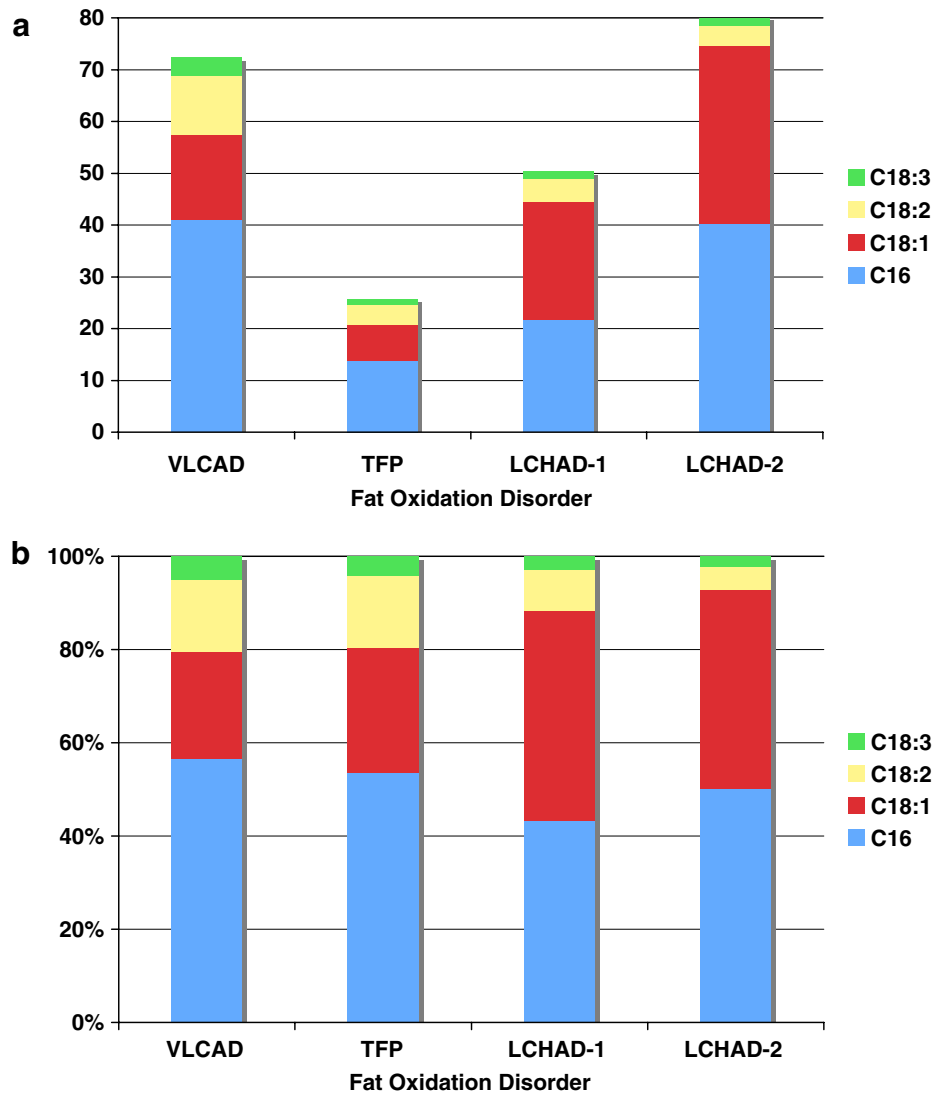


Fig. 1. (a) Contribution of fatty acids to disease-specific acylcarnitines in fibroblasts from long-chain fat oxidation disorders following 72 h incubations. (b) Percent of disease-specific acylcarnitines derived from individual fatty acid precursors, in vitro. C18:3 (α -linolenate), C18:2 (linoleate), C18:1 (oleate), and C16 (palmitate).

LCHAD: 30.4 (mean 88.3; range 68.5–108.1), and Thio-
lase: 21.8 (mean 25.0; range 17.3–32.7).

Each cell line was incubated separately for 72 h with equimolar (0.2 mM) concentrations of palmitate, oleate, linoleate and α -linolenate to determine their relative contributions to abnormal metabolites. The total and individual long-chain acylcarnitines produced from these in vitro incubations are represented in Fig. 1a. The TFP cell line produced the least amount of acylcarnitines from these fatty acid substrates (25.7 nmol/mg protein/72 h) compared to VLCAD (72.3), LCHAD-1 (50.3), and LCHAD-2 (80.3). Normal cells produced only 4.4 nmol/mg protein/72 h.

Despite the relative differences in total acylcarnitines, it is obvious that for any individual defect, the majority are derived from the non-essential fats, palmitate and oleate (C16 and C18:1, respectively) with lesser amounts derived from linoleate (C18:2) and the least from α -linolenate

(C18:3). This was also observed with normal cells even with the considerably lower levels. The percent contribution for each of the fatty acid substrates to these disease related acylcarnitines is presented in Fig. 1b and Table 2. In each defect, the non-essential fats (palmitate and oleate) produced the largest contributions to the acylcarnitines—between 80 and 94% with an average of 86%. Palmitate's contribution ranged from 46% for LCHAD to 57% for VLCAD while oleate ranged from 23% in VLCAD to 43% in LCHAD. The combined contributions from both

Table 2
Percent of total abnormal acylcarnitines

Cell line	VLCAD	TFP	LCHAD-1	LCHAD
Palmitate	57	56	46	51
Oleate	23	26	43	43
Linoleate	16	14	8	5
α -Linolenate	5	3	3	2

linoleate and α -linolenate (essential fats) to their total metabolites ranged from 7% to 21%. Linoleate's individual contributions ranged from 5% for LCHAD to 16% for VLCAD. The range for α -linolenate was only 2% for LCHAD with a maximum of 5% with the VLCAD cell line. There appeared to be a progressively decreased contribution to acylcarnitine metabolites for all cell line incubations as the number of double bonds in the fatty acid increased (C18:1–C18:3) Table 2.

Two of the patients studied (VLCAD and TFP) consented to an evaluation of essential fatty acid supplements comparing Canola oil to a combination of Flaxseed and Walnut oils. Both patients received the bulk of their daily caloric requirements via gastrostomy. The diets were designed to provide equivalent amounts of linoleate and α -linolenate (3% and 1% of daily caloric intake, respectively). Due to its composition, the amount of Canola oil required to meet the essential fatty acid needs contained much greater quantities of non-essential fats compared to the Flax/Walnut supplement. The patients received these supplemented diets for 3 days at which time the blood acylcarnitines were measured to determine if there was any difference in their levels with these two oil supplements. Table 3 reveals that the use of the Flax/Walnut oil with the least non-essential fats produced a decrease in circulating acylcarnitines from 33% to 36%. This decrease paralleled the results observed with the fibroblasts from these two patients.

Discussion

Dietary supplementation of essential fatty acids for patients requiring fat restricted diets has relied on commercially available oils for both convenience and reducing expense. Currently, for patients with long-chain fat oxidation defects the diet is either restricted fat and increased carbohydrate or supplemental medium-chain triglyceride oil. In either case, supplementation of essential fats is routinely provided [2]. These oil supplements often contain large quantities of non-essential fats (palmitate, stearate, and oleate) that are not effectively oxidized due to the genetic defect (Table 1). As illustrated in Fig. 1b and Table 2, these non-essential fatty acids are responsible

Table 3
Effect of reducing non-essential long-chain fatty acids on blood spot acylcarnitine levels (μM)

	Limit	Canola	Flax/Walnut	Change (%)
<i>VLCAD patient</i>				
C14:1	<0.14	2.74	1.78	(–35)
C16	<1.97	2.30	1.80	(–22)
C18:1	<2.64	3.53	2.15	(–39)
<i>TFP Patient</i>				
C14:1	<0.14	0.45	0.03	(–93)
C16	<1.97	1.38	0.95	(–31)
C16–OH	<0.06	0.18	0.06	(–67)
C18:1	<2.64	2.14	1.64	(–23)
C18:1–OH	<0.05	0.15	0.06	(–60)

for 80–94% (average = 86%) of abnormal acylcarnitines compared to only 7–21% (average = 14%) derived from the essential fats in vitro. The acylcarnitine contributions from the *unsaturated* fatty acids decreased in each of the disorders with increasing unsaturation of the 18 carbon fatty acids: cis-9- > cis-9,12- > cis-9,12,15-C18. On average, the contributions were 34%, 11%, and 3%, respectively, Table 2. After entry into the cell, all fatty acids must become substrates for the acyl-CoA synthetase to either enter into either cytosolic synthesis or mitochondrial β -oxidation. For the latter, they must be converted to acylcarnitines by action of carnitine palmitoyltransferase I (CPT I). CPT I is considered to be the “gatekeeper” that controls both further oxidation or synthesis. The substrate specificity and kinetics of CPT I with the different unsaturated C18 compounds has not been systematically studied. Since the cis- double bond creates a rigid 30° angle in the carbon chain, it is likely that these configurational changes due to increasing unsaturation found in oleate (cis-9), linoleate (cis-9,12), and α -linolenate (cis-9,12,15) could reflect a decreasing affinity of CPT I for these fatty acids. This possibility may be responsible for directing the essential fatty acids more to cytosolic synthesis after activation.

These disease related acylcarnitines are all derived from mitochondrial acyl-CoA intermediates. Due to the high concentration of L-carnitine (0.4 mM) in the incubations, acylcarnitines are preferentially formed thus preventing any marked increase in the intra-mitochondrial acyl-CoA to free Co-enzyme A (CoA) ratio. This ratio is increased, in vivo, when fasting or infection stimulates lipolysis in patients with these disorders. This may produce toxic effects on citric acid cycle function, compromised energy production via the electron transport chain, and activation of AMP-mediated protein Kinase (AMPK) [10]. Enhanced acyl-CoA:CoA ratio is also known to inhibit pyruvate dehydrogenase and α -keto-glutarate dehydrogenase complexes [11].

The relative amounts of non-essential fats included in the diet supplements are clearly not of the same magnitude as experienced in vivo during lipolysis but it is clear that disease-specific metabolites are consistently present as blood acylcarnitines in patients. However, it is not known if these compounds, at those levels, exert any kind of chronic pathologic effect. The trials with 2 patients alternating with Canola versus Flax/Walnut oils as essential supplements to their gastrostomy feedings did support the notion that excessive non-essential fats in the supplement should be avoided. The 33–36% reduction in disease-specific blood acylcarnitines with the Flax/Walnut supplement reflects this and suggests that improved diet therapy can be achieved Table 3. It is unfortunate that an economical preparation is not available that contains only linoleate and α -linolenate in the appropriate ratio.

Consideration of the clinical course of these disorders suggests that even low levels of some metabolites may have a pathologic role. Peripheral neuropathy is a severe feature of TFP deficiency and less severe with LCHAD deficiency. Peripheral neuropathy is not observed in the other long-

chain disorders. The acylcarnitines observed with TFP and LCHAD deficiencies appear identical by blood acylcarnitine analysis and in vitro incubation of fibroblasts with $16\text{-}^2\text{H}_3\text{-palmitate}$. In both cases, one observes elevation of palmitoylcarnitine and to a lesser extent its 3-OH derivative. TFP can now be distinguished reliably from LCHAD deficiency by in vitro incubation with pristanate that is oxidized first in the peroxisome followed by final oxidation in the mitochondrion. The ratio of dimethylnonanoylcarnitine (C11) to dimethylheptanoylcarnitine (C9) is considerably greater in TFP deficiency than with LCHAD cell lines [12]. The enzyme assay results from the patient in this study revealed the greatest deficiency in thiolase activity as opposed to the isolated LCHAD deficient cell lines. LCHAD deficiency prevents the conversion of L-3-OH-acyl-CoA to the 3-keto-acyl-CoA intermediate, normally a reversible reaction. In TFP deficiency due to absent thiolase activity, the 3-keto-acyl-CoA intermediate can be reduced to the L-3-OH-acyl-CoA by the LCHAD enzyme or, as the free keto-acid, it can be spontaneously decarboxylated to a methylketone (e.g. 3-keto-palmitate to 2-ketopentadecane) (Fig. 2). Methylketones are not observed by organic acid analysis since there is no hydroxyl- or carboxyl- group to derivatize. Only in 2-methyl-acetoacetyl-CoA thiolase deficiency (β -ketothiolase), in the isoleucine pathway, has a methyl ketone, 2-butanone been detected. It is the decarboxylated product of 2-methyl-acetoacetate [13]. Severe peripheral neuropathy has been previously studied in workers in chemical plants manufacturing hexane. It was shown that the metabolism of hexane produces a γ -diketone (2,5-hexanedione) that forms covalent bonds with lysyl residues of myelin. This interrupts axonal flow resulting in a peripheral neuropathy and myopathy [14,15]. Since the etiology of the more severe peripheral neuropathy in TFP deficiency remains unknown, we hypothesize that the neuropathy may be related to the fate of a unique metabolite such as the 3-keto acids that accumulate. For these reasons as well as the observations that the 3-OH-acylcarnitines are always increased in blood acylcarnitine analysis from these patients, it may be useful to further reduce their occurrence

by substantial reduction in dietary non-essential fatty acids. The reduced production of abnormal acylcarnitines, in vitro, by the essential fatty acids and decreased blood levels of all acylcarnitines resulting from the Flax/Walnut supplement, compared to Canola, seem to support this strategy.

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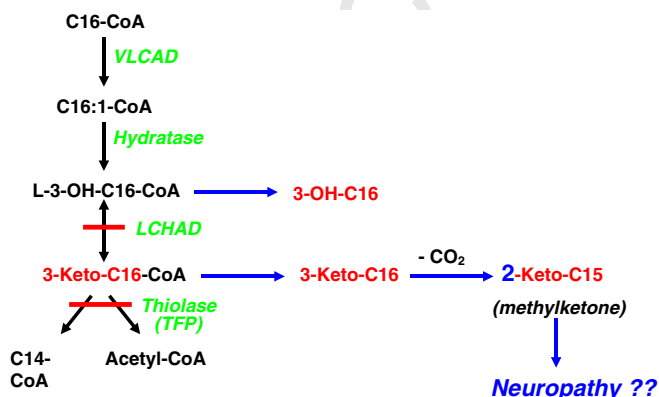


Fig. 2. Metabolites of palmitoyl-CoA (C16-CoA) produced by deficiencies of LCHAD and the thiolase portion of the trifunctional protein. Proposed relationship of methylketones and peripheral neuropathy.