Recycling of docosahexaenoic acid in rat retinas during n-3 fatty acid deficiency

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Abstract About 50% of the fatty acids in retinal rod outer segments is docosahexaenoic acid [22:6(n-3)], a member of the linolenic acid [18:3(n-3)] family of essential fatty acids. Dietary deprivation of n-3 fatty acids leads to only modest changes in 22:6(n-3) levels in the retina. We investigated the mechanism(s) by which the retina conserves 22:6(n-3) during n-3 fatty acid deficiency. Weanling rats were fed diets containing 10% (wt/wt) hydrogenated coconut oil (no n-3 or n-6 fatty acids), linseed oil (high n-3, low n-6), or safflower oil (high n-6, <0.1% n-3) for 15 weeks. The turnover of phospholipid molecular species and the turnover and recycling of 22:6(n-3) in phospholipids of the rod outer segment membranes were examined after the intravitreal injection of [2-^{3}H]glycerol and [4,5-^{3}H]22:6(n-3), respectively. Animals were killed on selected days, and rod outer segment membranes, liver, and plasma were taken for lipid analyses. The half-lives (days) of individual phospholipid molecular species and total phospholipid 22:6(n-3) were calculated from the slopes of the regression lines of log specific activity versus time. There were no differences in the turnover rates of phospholipid molecular species among the three dietary groups, as determined by the disappearance of labeled glycerol. Thus, 22:6(n-3) is not conserved through a reduction in phospholipid turnover in rod outer segments. However, the half-life of [4,5-^{3}H]22:6(n-3) in the linseed oil group (19 days) was significantly less than in the coconut oil (54 days) and safflower oil (not measurable) groups. Analysis of plasma, liver, and the contralateral (non-injected) eye showed that the specific activity of 22:6(n-3) was less than 1% of the 22:6(n-3) in the injected eye. These results suggest that, during n-3 deficiency, the retina conserves 22:6(n-3) by recycling this fatty acid within the eye.—**Stinson, A. M., R. D. Wiegand, and R. E. Anderson.** Recycling of docosahexaeonic acid in rat retinas during n-3 fatty acid deficiency. *J. Lipid Res.* 1991. **32:** 2009-2017.

Supplementary key words polyunsaturated fatty acids • rod outer segments • essential fatty acids • phospholipids • lipids • membrane lipids

The outer segment of the photoreceptor cell is a highly structured organelle responsible for absorbing light and initiating visual excitation. The rod outer segment consists of stacks of hundreds of membranous discs, which are surrounded by a plasma membrane joined to the inner segment through a connecting cilium. The inner segment contains the nucleus, endoplasmic reticulum, mitochondria, and Golgi apparatus. The presence of these organelles indicates that the inner segment is the metabolic machinery of the photoreceptor cell.

Rod outer segment membranes have a rather simple lipid composition (1). The major phospholipids are phosphatidylcholine (PC), phosphatidylethanolamine (PE), and phosphatidylserine (PS), which account for more than 90% of the total phospholipids. The minor components are phosphatidylinositol, phosphatidic acid, and sphingomyelin, which make up the rest of the phospholipids. The most striking feature of rod outer segment membranes is the presence of large amounts of docosahexaenoic acid [22:6(n-3)], which generally comprises about half of the fatty acids of PE and PS (1). In addition, PC, PE, and PS of rod outer segments from a variety of animal species contain large amounts of dipolyunsaturated molecular species, especially 22:6(n-3)-22:6(n-3) (1-6).

Docosahexaenoic acid and its shorter chain precursors are essential fatty acids. Animals cannot synthesize these fatty acids, so they must be obtained from the diet. Since mammalian rod outer segment discs are completely renewed every 10 days (7), one would expect that prolonged dietary deprivation of these essential fatty acids would lead to the depletion of 22:6(n-3) from these membranes. However, rats (8-10) raised on n-3- and n-6-deficient diets and monkeys raised on n-3-deficient diets (11-13) showed only slight decreases in the 22:6(n-3) content of their rod outer segments or retinas. These observations indicate that the retina has the ability to conserve 22:6(n-3) during fatty acid deficiency.

We have previously tested and rejected several hypotheses for the conservation of 22:6(n-3) by the retina (14): *a*) the retina is capable of de novo synthesis of

Abbreviations: PUFA, polyunsaturated fatty acid; PC, phosphatidylcholine; PS, phosphatidylserine; PE, phosphatidylethanolamine; DGBZ, diacylglycerobenzoate; FAPE, fatty acid phenacyl esters; HPLC, high performance liquid chromatography; GLC, gas-liquid chromatography.

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22:6(n-3) (15); *b*) the retina can reduce the requirements for 22:6(n-3) by either shortening the lengths of the rod outer segments or reducing the number of photoreceptor cells (14); and *c*) there is a reduction in the renewal rate of rod outer segment discs in the absence of a dietary source of 22:6(n-3) or its precursors (14).

In the present study, we have tested four additional conservation hypotheses: *a*) there is a decrease in the turnover rate of 22:6(n-3)-containing molecular species of rod outer segment phospholipids during n-3 fatty acid deficiency; *b*) there is a reduction in the turnover rate of 22:6(n-3) esterified in phospholipids of rod outer segment membranes; *c*) the retina can selectively sequester from the blood the small amount of 22:6(n-3) that is present during n-3 fatty acid deficiency; and *d*) there is a recycling of 22:6(n-3) (*i*) within the retina, (*ii*) between the retina and retinal pigment epithelium, or (*iii*) among the retina, the retinal pigment epithelium, and the blood. Our results indicate that 22:6(n-3) is conserved by recycling within the eye.

EXPERIMENTAL PROCEDURES

Animals

Weanling Long Evans female and adult (3-4 months) rats were obtained from Charles River (Wilmington, MA) and housed under cyclic lighting conditions (12L:12D) at an illumination of 200-300 lux. Adult rats were fed rat chow, while weanling rats were divided randomly into three groups and fed a semisynthetic diet (AIN-76A Basal Diet containing 0.02% tertiary butylhydroquinone, an antioxidant, Dyets, Inc., Bethlehem, PA) supplemented with either 10% (wt/wt) hydrogenated coconut oil, 10% (wt/wt) linseed oil, or 10% (wt/wt) safflower oil for 15 weeks. Animals were anesthetized with Nembutal (40 mg/kg body weight IP) and injected intravitreally with either 5 μl (20 μCi) of [2-^{3}H]glycerol (sp act 200 mCi/mmol in sterile aqueous solution, ICN Radiochemicals, Irvine, CA) or 2 μl (20 μCi) of [4,5-^{3}H]docosahexaenoic acid (sp act 23.0 Ci/mmol in 100% ethanol, New England Nuclear). After injection, animals were maintained on their respective diets in a metabolic chamber (Freas Model 818, Precision Scientific, Chicago, IL) under cyclic light until they were killed.

Dietary oils and weight gain of animals

Diets were formulated and pelleted by Dyets Inc., shipped by air express, and stored at −20°C until used. Pellets of each diet were extracted and their fatty acid compositions were determined (14). The hydrogenated coconut oil was comprised mainly of saturated fatty acids such as 12:0, 14:0, 16:0, and 18:0. Unlike coconut oil, the linseed oil contained polyunsaturated fatty acids (PUFAs), primarily 18:3(n-3) (53%) and 18:2(n-6) (20%). The major fatty acid of the safflower oil was 18:2(n-6) (83%). Only a trace amount (<0.1%) of 18:3(n-3) was found in the safflower oil diet. Therefore, the coconut oil diet was an essential fatty acid-deficient diet, containing neither n-3 nor n-6 fatty acids. The linseed oil diet was an n-3 fatty acid-supplemented diet, whereas the safflower oil diet was an n-6 fatty acid-supplemented (n-3 deficient) diet. Pellets of the linseed oil diet did not show any loss of 18:3(n-3) after 4 days at room temperature. Therefore, the diets were completely replaced twice a week during the 15-week feeding period.

The weights of the rats fed the three diets were measured weekly (data not shown). There was no significant difference in weight gains between groups, although an increase in the levels of 20:3(n-9) in the plasma of rats fed the coconut oil diet indicated that they were deficient in n-6 fatty acids.

Preparation of tissues

Blood removed via cardiac puncture was collected in heparinized tubes and allowed to sit on ice for 30 min. Blood elements were removed by centrifugation at 1500 rpm for 20 min and the plasma was collected. A portion of the liver was removed, blotted, and frozen. Rod outer segments were prepared as previously described (16).

Lipid extraction and separation

Lipids of rod outer segment membranes, plasma, and liver homogenates were extracted according to the procedure of Bligh and Dyer (17). The lipid extract was dried under N_2 at room temperature and resolved either into individual phospholipid classes by two-dimensional TLC on silica gel HR (18) or into total phospholipids and neutral lipids by one-dimensional TLC using a KG silica gel plate (10 × 20 cm, 250 μm, Whatman) in a solvent system of hexane-diethyl ether-acetic acid 75:35:1 (by volume). The lipid spots were visualized by spraying the chromatoplate with 0.05% 2',7'-dichlorofluorescein in aqueous methanol (75%) and viewing under UV light. Regions on the chromatoplates corresponding to the individual lipid classes were scraped from the plates, butylated hydroxytoluene (BHT, 250 μg) was added, and the lipids were extracted according to the procedure described by Arvidson (19).

Lipid derivatization

The diacylglycerobenzoate derivatives (DGBZ) of rod outer segment PC and PE were prepared as described by Louie, Wiegand, and Anderson (5). Recovery of DGBZ prepared by this method is 80-85% (20). Fatty acid phenacyl esters (FAPE) were prepared using the procedures of Wood and Lee (21) and Hanis et al. (22).

HPLC separation of lipid derivatives

Chromatography of the 1,2-DGBZ molecular species from rod outer segment PC and PE was accomplished by HPLC on a Supelcosil LC-18 column (25 cm × 4.6 mm I.D.). The mixture of 1,2-DGBZ molecular species dissolved in 80–90 μl of acetonitrile–2-propanol 80:20 (by volume) was injected into the column and separated by isocratic elution. The flow rate was 1.0 ml/min and the molecular species were detected by monitoring the absorbance at 230 nm. Identification and quantification of the DGBZ molecular species were accomplished as described by Louie et al. (5).

Separation of FAPE of total phospholipids of rod outer segments was carried out according to the procedures of Wood and Lee (21). The FAPE were eluted with a linear gradient of acetonitrile–water 80:20 to 90:10 (by volume) over 45 min at a flow rate of 2 ml/min. The mobile phase was held at 90:10 for 5 min and then returned to the 80:20 mixture. The eluted FAPE were detected at 242 nm.

Radiolabeled fatty acids were detected using a Radiomatic Flo-One/Beta Series A-250 radioactivity detector (Radiomatic Instruments, Tampa, FL). After emerging from the UV detector, the eluate from the HPLC was mixed with scintillation cocktail (ScintiVerse LC, Fisher Scientific) in a ratio of 1:3 (eluate–scintillation cocktail, by volume) and counted in a 1.5-ml flow cell at 6-sec intervals.

Statistical analysis

The least squares regression lines of selected molecular species from PC and PE and of 22:6 (n–3) in total phospholipids of rod outer segments were obtained from plots of log specific activity versus time (days). The significance of each regression line, or the functional dependence of log specific activity on time, was first tested using Analysis of Variance. The slopes of the regression lines from the three dietary groups were then compared using Analysis of Covariance.

RESULTS

Turnover of rod outer segment phospholipid molecular species after intravitreal injection of [2-^{3}H]glycerol

Weanling rats fed coconut oil, linseed oil, or safflower oil diets for 15 weeks were injected intravitreally with [2-^{3}H]glycerol and killed at 1, 2, 3, 4, and 6 days post-injection. Rod outer segment phospholipids were isolated, derivatized, and fractionated into individual molecular species by HPLC. Peaks eluted from HPLC were quantitated and counted for radioactivity. HPLC tracings of PC and PE molecular species from rats fed the three diets are presented in **Fig. 1**. Since the separation of the DGBZ by reverse-phase HPLC is based on the length of the carbon

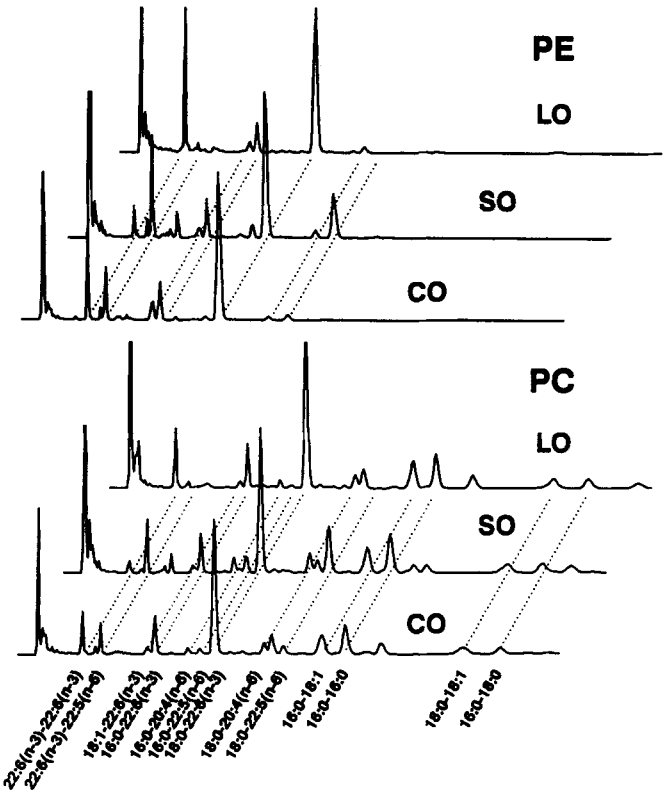

Fig. 1. HPLC tracings of the diacylglycerobenzoate (DGBZ) molecular species derived from PC and PE of rod outer segments. The separation of individual DGBZ molecular species was achieved on a C-18 reverse phase column with a solvent of acetonitrile–isopropanol 80:20 (by volume) and detected at 230 nm. The elution time for 16:0–18:0 was approximately 60 min. The abbreviations used in the figures are: LO, linseed oil; CO, coconut oil; and SO, safflower oil.

chain and the degree of unsaturation, the didocosahexaenoic species, 22:6(n–3)–22:6(n–3), was the first peak identified after the solvent front. The next major peak was identified as 22:6(n–3)–22:5(n–6); however, GLC analysis showed a multiplicity of coeluting molecular species, with 22:6(n–3)–22:5(n–6) as the major component. Other species found in both PC and PE were 18:1(n–9)–22:6(n–3), 16:0–22:6(n–3), 16:0–20:4(n–6), 16:0–22:5(n–6), 18:0–22:6(n–3), 18:0–20:4(n–6), and 18:0–22:5(n–6). Saturated and monoenoic-saturated species, such as 18:1(n–9)–16:0 and 16:0–16:0, were present only in PC.

HPLC tracings of PC and PE molecular species from the safflower oil and the coconut oil groups showed a decrease in the levels of 22:6(n–3)–22:6(n–3) and an increase in the levels of 22:5(n–6)- and 20:4(n–6)-containing molecular species, such as 22:6(n–3)–22:5(n–6), 18:0–22:5(n–6), 16:0–22:5(n–6), 18:0–20:4(n–6), and 16:0–20:4(n–6). These increased levels of 22:5(n–6)- and 20:4 (n–6)-containing molecular species compensated for and replaced the lower levels of 22:6(n–3)-containing species in the safflower oil and the coconut oil groups. Quantitative analysis of the lipids from rats fed these three diets has been published (14).

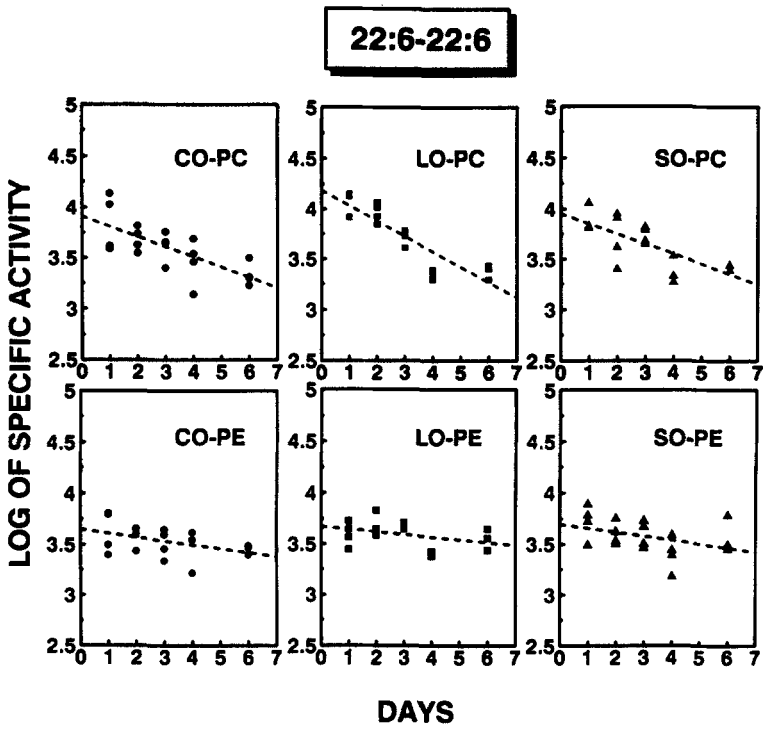

Fig. 2. Linear regression plots of log specific activity of 22:6(n-3)-22:6(n-3) molecular species from the three dietary groups. Animals were injected intravitreally with [2-^{3}H]glycerol and killed on days 1, 2, 3, 4, and 6. PC and PE of rod outer segments were separated, derivatized, and fractionated into individual molecular species by HPLC (See Fig. 1). The peak containing 22:6(n-3)-22:6(n-3) was quantitated, collected, and counted for radioactivity. Specific radioactivity is expressed as DPM/nmol fatty acid.

The turnover rates of individual molecular species of rod outer segment phospholipids were determined by following the exponential decay of the radioactivity after an intravitreal injection of [2-^{3}H]glycerol. Plots of log specific activity versus time of two major molecular species of the rod outer segments, 22:6(n-3)-22:6(n-3) and 18:0-22:6(n-3), are shown in **Fig. 2** and **Fig. 3**, respectively. As demonstrated previously (5, 23, 24), PC is metabolically more active than PE, as indicated by the faster turnover of these two molecular species in PC. The same observation was made for the other 22:6(n-3)-containing molecular species, 16:0-22:6(n-3),

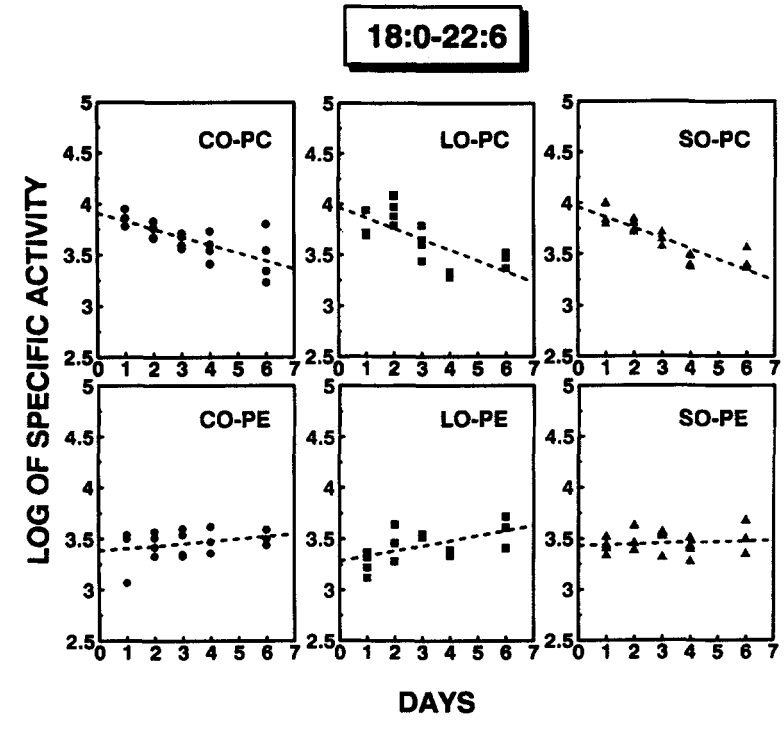

Fig. 3. Linear regression plots of log specific activity of 18:0-22:6(n-3) molecular species from the three dietary groups. Animals were injected intravitreally with [2-^{3}H]glycerol and killed on days 1, 2, 3, 4, and 6. PC and PE of rod outer segments were separated, derivatized, and fractionated into individual molecular species by HPLC (See Fig. 1). The peak containing 18:0-22:6(n-3) was quantitated, collected, and counted for radioactivity. Specific radioactivity is expressed as DPM/nmol fatty acid.

18:1-22:6(n-3), and 22:6(n-3)-22:5(n-6) (data not shown). The turnover rates of the same 22:6(n-3)-containing molecular species from the three dietary groups were compared using Analysis of Covariance. The *P*-values resulting from the pair-wise comparisons (coconut oil vs. linseed oil, coconut oil vs. safflower oil, and linseed oil vs. safflower oil) showed no significant differences between dietary groups at the 0.05 level.

Turnover of docosahexaenoic acid in rod outer segment phospholipids after intravitreal injection of [4,5-^{3}H]22:6(n-3)

Rats raised on the coconut oil, linseed oil, or safflower oil diet for 15 weeks were injected intravitreally with [4,5-^{3}H]22:6(n-3) and killed on days 6, 12, 24, 36, 48, and 60. **Fig. 4** shows absorbance (solid line) and radioactivity (dashed line) tracings of FAPE of rod outer segment total phospholipids from rats fed the three diets and killed 60 days after injection. A simple, but rather striking, radiolabeling pattern was observed, with almost all of the label in 22:6(n-3). The label remained in this fatty acid throughout the 60-day period, indicating that no chain shortening or retroconversion occurred in the retina during this time.

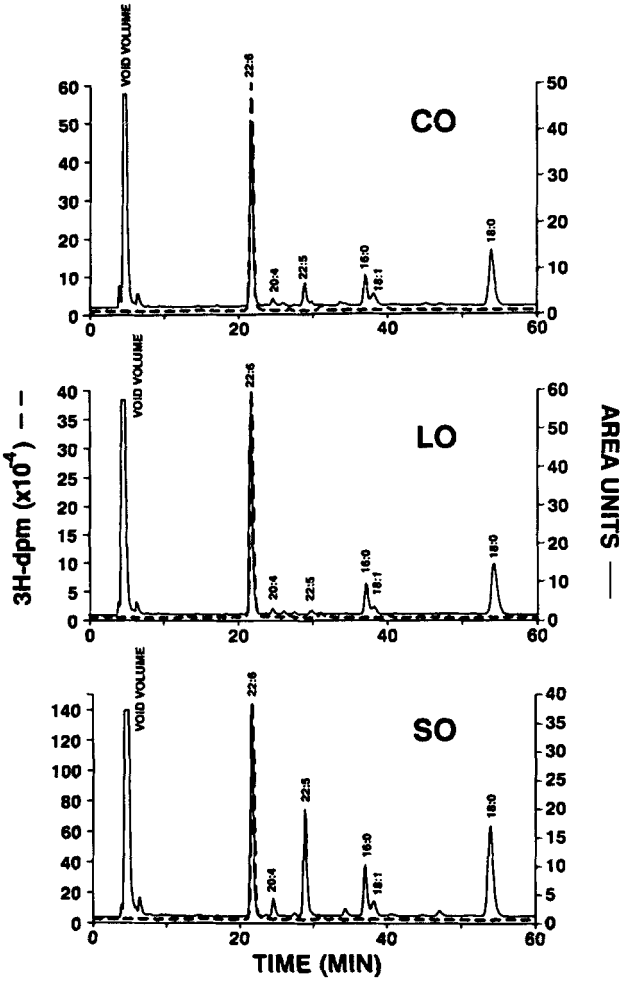

Fig. 4. Absorbance (solid line) and radioactivity (dashed line) tracings of FAPE derived from rod outer segment total phospholipids. Rats fed coconut oil, linseed oil, or safflower oil diets for 15 weeks were injected intravitreally with [4,5-^{3}H]22:6(n-3) and killed on selected days. FAPE of the rod outer segment total phospholipids were separated and quantitated by HPLC. Radioactivity was counted using a Radiomatic Flo-One/Beta Series A-250 radioactivity detector.

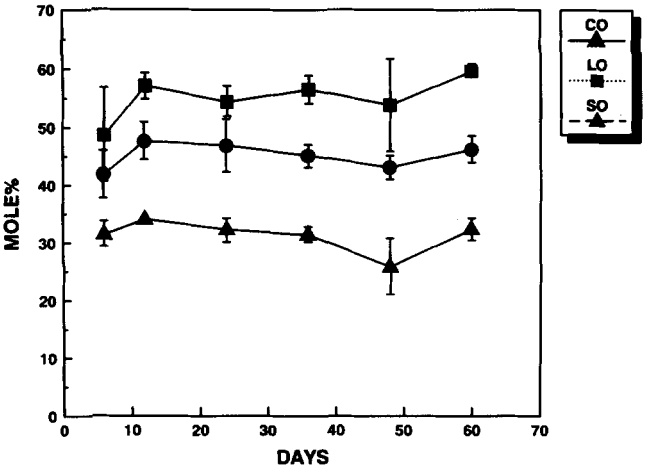

Fig. 5. The mole percent of 22:6(n-3) in rod outer segment total phospholipids from rats fed the coconut oil, linseed oil, or safflower oil diets. The values are the average ± SD of four independent analyses from four rats.

The mass of six identified fatty acids eluting from the HPLC (Fig. 4) was determined and normalized to give relative mole%. **Fig. 5** shows that the mole% of 22:6(n-3) from the three dietary groups did not change over the 60-day post-injection period. However, differences were observed in the mole% of 22:6(n-3) between the dietary groups. The relative amount of 22:6(n-3) was highest in the linseed oil group (55-60%), lowest in the safflower oil group (30-35%), and intermediate in the coconut oil group (40-45%).

The turnover of docosahexaenoic acid in rod outer segment phospholipids was determined by following the exponential decay of the radioactivity after intravitreal injection of [4,5-^{3}H]22:6(n-3). The rate of turnover is represented by the half-life, which can be calculated from the slope of the linear regression line of log specific activity versus time. **Fig. 6** shows the plots of log specific activity of 22:6(n-3) versus time for the three groups. The parameters of these regressions and calculated half-lives are given in **Table 1**. As determined from the *P*-value (0.9638) and R^2 (0.000), the regression line from the safflower oil group showed no dependent relationship between log specific activity and time. The slope of this regression line was not significantly different from zero, indicating that there was no measurable turnover of 22:6(n-3) in this group. However, the regression lines from both the coconut oil and the linseed oil groups were

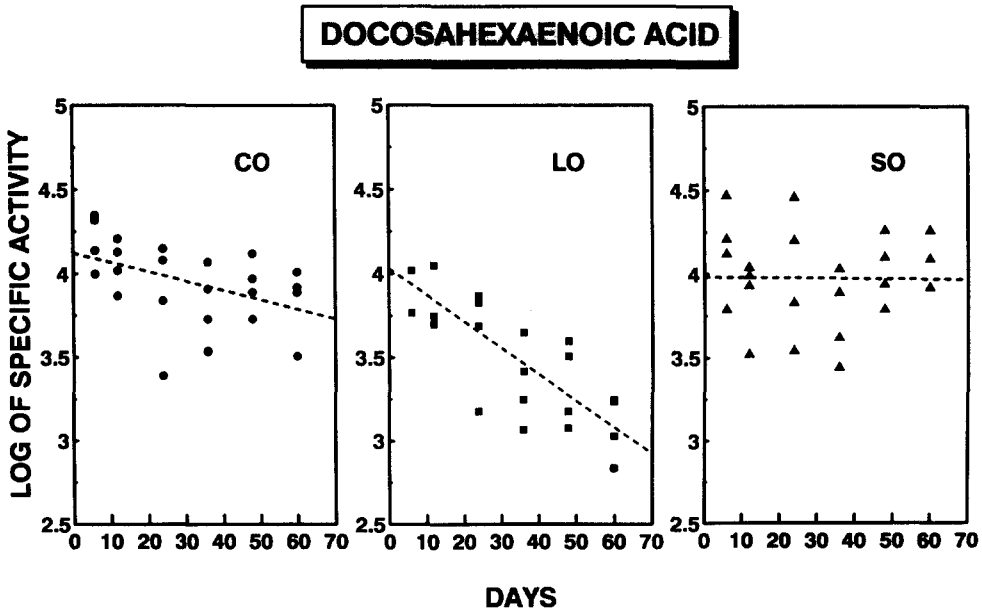

Fig. 6. Linear regression plots of log specific activity of 22:6(n-3) in rod outer segment total phospholipids versus time. Rats fed the coconut oil, linseed oil, or safflower oil diets for 15 weeks were injected intravitreally with [4,5-^{3}H]22:6(n-3) and killed on selected days. FAPE of rod outer segment total phospholipids were quantitated by HPLC and radioactivity was determined with a Radiomatic Flo-One/Beta radioactivity detector. Specific activities were calculated and their log values plotted versus time. Each time point contains four independent determinations of two pooled retinas from four individual rats.

significant. The linseed oil group had the fastest turnover of 22:6(n-3), with a half-life of 19 days. The coconut oil group turned over its 22:6(n-3) at a much slower rate, with a half-life of 54 days.

The differences in the turnover rates of 22:6(n-3) from the three dietary groups were determined by comparing the slopes of the regressions using Analysis of Covariance. A *P*-value of 0.0005 suggested the significant difference between these three dietary groups and prompted follow-up pair-wise comparisons. As shown in Table 1, the linseed oil group was significantly different from the coconut oil and the safflower oil groups (linseed oil vs. coconut oil, $P = 0.0043$; linseed oil vs. safflower oil, $P = 0.0004$). However, there was no significant difference between the coconut oil and safflower oil groups ($P = 0.1779$).

Recycling of docosahexaenoic acid

The slower turnover rate of 22:6(n-3) in the coconut oil and safflower oil groups indicated that this fatty acid was not lost from the retina during n-3 deficiency. Recycling of 22:6(n-3) between the retina, the retinal pigment epithelium, and the blood was tested by injecting

TABLE 1. Linear regression analysis of the turnover of [4,5-^{3}H]22:6(n-3) from rod outer segment total phospholipids

Diet	Slope	SE Slope	P[a]	R^2	T1/2[b]	P[c]
	days^{-1}	*days*$^{-1}$			*days*	
Coconut oil	−.0056	.0024	.0270	.203	54.0	
Linseed oil	−.0158	.0024	.0000	.666	19.0	
Safflower oil	−.0003	.0032	.9638	.000	ND	
Coconut oil vs. linseed oil						.0043
Coconut oil vs. safflower oil						.1779
Linseed oil vs. safflower oil						.0004

[a]The functional dependence of log specific activity on time was tested using Analysis of Variance. A *P*-value less than 0.05 indicates that the slope is significantly different from zero.

[b]The turnover rate of [4,5-^{3}H]22:6(n-3) is presented as the half-life, calculated from the slope of a linear regression ($T_{1/2}$ = log 2/slope) plotting log specific activity of 22:6(n-3) versus time. No half-life could be calculated for the safflower oil group (ND).

[c]The difference in the turnover rates of [4,5-^{3}H]22:6(n-3) among the coconut oil, linseed oil, and safflower oil groups was determined by comparing the slopes using Analysis of Covariance. *P*-values less than 0.05 indicate that the slopes are different.

[4,5-^{3}H]22:6(n-3) intravitreally into the right eye of rats and monitoring the appearance of radioactivity in contralateral (uninjected) eye, plasma, and liver, 6 and 22 days post-injection. At both time points, the specific radioactivity of 22:6(n-3) from rod outer segment phospholipids from the injected eye was several hundred times greater than in the uninjected eye, plasma, or liver (**Fig. 7**).

DISCUSSION

The retina has the ability to conserve its high level of 22:6(n-3) during n-3 and/or n-6 fatty acid deficiency (8-14). The mechanism of conservation is not known, although several hypotheses have been proposed (14): *a*) the retina is capable of de novo synthesis of 22:6(n-3); *b*) the retina can reduce the requirements for 22:6(n-3) by either shortening the lengths of the rod outer segments or reducing the number of photoreceptor cells; *c*) there is a reduction in the renewal rate of rod outer segment discs in the absence of a dietary source of 22:6(n-3); *d*) there is a decrease in the turnover rate of 22:6(n-3)-containing molecular species of rod outer segment phospholipids during n-3 fatty acid deficiency; *e*) there is a reduction in the turnover rate of 22:6(n-3) in phospholipids of rod outer segment membranes; *f*) the retina can selectively sequester from the blood the small amount of 22:6(n-3) that is present during n-3 fatty acid deficiency; and *g*) there is a recycling of 22:6(n-3) (*i*) within the retina, (*ii*) between the retina and retinal pigment epithelium, or (*iii*) among the retina, the retinal pigment epithelium, and the blood. Hypotheses *a-c* were tested in previous studies and rejected (14, 15).

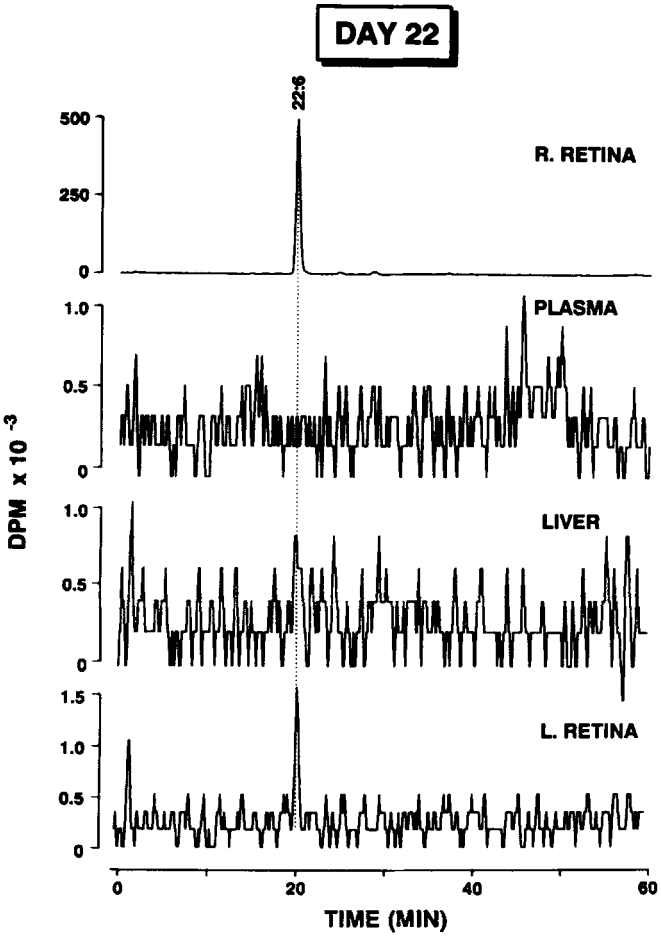

Fig. 7. Radioactivity tracings of the FAPE of total lipids derived from rod outer segment membranes of the injected eye (R. Retina), the uninjected eye (L. Retina), plasma, and liver 22 days after intravitreal injection of [4,5-^{3}H]22:6(n-3). The FAPE of the total lipids were separated and quantitated by HPLC. Radioactivity was counted using a Radiomatic Flo-One/Beta Series A-250 radioactivity detector.

It has been well established that phospholipids of rod outer segment membranes are in a dynamic state of rapid turnover (5, 23, 24). Also, different molecular species within a phospholipid class or the same species between different phospholipid classes have different turnover rates (5, 24). In general, when [^{3}H]glycerol is used to label rod outer segment phospholipids, there is rapid turnover of PC species, intermediate turnover of PE species, and slow turnover of PS species. The results of the present study confirm and extend these reports. However, between the three diet groups, no significant differences were found in the turnover rates of 22:6(n-3)-containing molecular species, as measured by the disappearance of radioactive glycerol (Figs. 2 and 3). We therefore reject the hypothesis (*d*) that the retina conserves 22:6(n-3) by lowering the turnover rates of 22:6(n-3)-containing phospholipid molecular species of rod outer segment membranes during n-3 deficiency.

Hypothesis (*e*), i.e., a reduction in the turnover rate of 22:6(n-3) in rod outer segment phospholipids, was tested by following the fate of [4,5-^{3}H]22:6(n-3) injected intravitreally. The half-life of 22:6(n-3) in the linseed oil group was 19 days, compared to 54 days in the coconut oil group. No half-life could be calculated for the safflower oil group. The renewal of integral proteins (14) and the turnover of glycerol in glycerolphospholipids (Figs. 2 and 3) of rod outer segments were not affected by n-3-deficiency. However, the differences in half-lives of labeled 22:6(n-3) indicate that the metabolism of this fatty acid is affected by diet. When n-3 fatty acids are readily available in the diet, 22:6(n-3) turns over in the retina either through oxidation or by returning to the circulation. However, in n-3 deficiency, 22:6(n-3) does not leave the retina. Rather, it is recycled, either within the retina via deacylation-reacylation pathways known to exist in rod outer segments (25, 26) or between the retina and the pigment epithelium.

Recent studies suggest that 22:6(n-3) is recycled between the retina and the pigment epithelium. Gordon and Bazan (27) injected radiolabeled 22:6(n-3) intravitreally

into frogs and monitored its cellular localization by autoradiography. The densities of silver grains over the distal tips of rod outer segments and outer segment phagosomes in the pigment epithelium were similar, leading them to suggest that 22:6(n-3) was present in the shed outer segment tips. Chen et al. (28) measured the molecular species of PC and PE in frog rod outer segments and pigment epithelium before and after light-induced shedding of outer segment tips. There was a significant increase in molecular species containing 22:6(n-3) in the pigment epithelium following the shedding event. If we apply these results to the present study, we would conclude that 22:6(n-3) is conserved in the retina through recycling between the retina and the pigment epithelium.

The results presented in Table 1 also provide information on hypothesis (*f*), i.e., that the retina can selectively sequester small amounts of 22-carbon PUFA from the blood during n-3 deficiency. If the retina incorporated unlabeled 22:6(n-3) from the blood during the 60 days of the study, the specific activities of 22:6(n-3) in the rod outer segments should decrease with time because of dilution of the label. Indeed, this occurred for the linseed oil group, but not for the safflower oil group. Therefore, we conclude that, although the retina can sequester 22:6(n-3) from the blood, there are limitations. During the early phase of n-3 fatty acid deficiency, the retina responds by sequestering 22:6(n-3) from the blood. However, during prolonged n-3 deficiency, the uptake of 22:6(n-3) from the blood is drastically reduced and the retina maintains its levels of 22:6(n-3) by recycling within the eye.

In summary, we have shown that the retina conserves 22:6(n-3) during n-3 fatty acid deficiency by retaining this fatty acid within the eye. On the basis of other studies (27, 28), we suggest that 22:6(n-3) is recycled between the retina and the pigment epithelium. The pigment epithelium must have a remarkably efficient system to direct the flow of fatty acids back to the retina, given the large amount of material that this tissue phagocytizes each day (10% of the rod outer segments). The mechanism(s) by which this highly selective flow of lipids between the pigment epithelium and the retina is achieved is not known. Proteins that bind retinoids have been identified in the retina (29), and cytosolic fatty acid binding proteins have been characterized in a number of tissues (30). It seems likely that the transfer of 22:6(n-3) and other fatty acids between the retina and the pigment epithelium would be mediated by some type of carrier protein.

Supported in part by grants from the National Institutes of Health (EY07001, EY00871, EY04149, and EY02520), the RP Foundation Fighting Blindness, the Retina Research Foundation, and Research to Prevent Blindness, Inc.

Manuscript received 3 July 1991 and in revised form 1 October 1991.

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