Comparison of FA Compositions of Selected Tissues of Phocid Seals of Eastern Canada Using One-Way and Multivariate Techniques

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ABSTRACT: The FA composition of selected tissues of all six species of eastern Canadian phocid seals: bearded seal (*Erignathus barbatus*), gray seal (*Halichoerus grypus*), harbor seal (*Phoca vitulina*), harp seal (*P. groenlandica*), hooded seal (*Cystophora cristata*), and ringed seal (*P. hispida*) was determined to detect possible differences among different tissues and species. A univariate approach was used to examine differences among different tissues and species separately, and a multivariate approach was taken in examining differences among different species and tissues simultaneously. Findings indicated that FA composition depended on both tissue and species of seal. However, differences were most apparent among tissues. Several unique features of the FA compositions were identified. Blubber was found to be high in the monounsaturated FA, but low in arachidonic acid and dimethyl acetals. Brain tissue lipids, on the other hand, were high in dimethyl acetals and DHA. Lung tissue lipids were very high in palmitic acid, and heart tissue lipids had a higher content of linoleic acid than did lipids of other tissues examined. Thus, the proportions of FA constituents in different tissues were different, most probably due to their varying functional requirements.

Paper no. J10168 in *JAOCS 79,* 1095–1102 (November 2002).

KEY WORDS: Brain lipids, heart lipids, kidney lipids, liver lipids, lung lipids, muscle lipids, seal blubber oil.

Interest in marine oils has continued since the 1970s when epidemiological studies suggested that low incidences of heart disease in Greenland Eskimos and some Japanese populations were due to their unique diets, which were rich in oily fish, whale blubber, and seal blubber (1,2). It is believed that humans traditionally consumed a diet with a ratio of n-6 to n-3 FA of about 1:1, whereas today the ratio is estimated to range from 10:1 to 25:1 in the Western diet (3). Therefore, Western diets are deficient in n-3 FA compared with the diet on which humans evolved and from which their genetic profiles were established (3). More recently, interest in seal oil, specifically as a source of n-3 FA, has intensified as more studies have revealed its potential health benefits (3).

The FA compositions of marine mammalian muscle tissue, blubber, and milk have been the subject of many investigations (5–19). The blubber of marine mammals, because of its economic importance, has been the subject of most studies on marine oils to date. No previous study has compared the FA compositions of different tissues from all six species of eastern Canadian seals. There are two families of seals, Phocidae and Otaridae. The Phocidae, or the true seals, are the ones found in the eastern Canadian waters, whereas the Otaridae, or eared seals, are not of interest in this study.

In this study, the FA compositions of selected tissues from all six species of eastern Canadian phocid seals, namely, the bearded seal (*Erignathus barbatus*), gray seal (*Halichoerus grypus*), harbor seal (*Phoca vitulina*), harp seal (*P. groenlandica*), hooded seal (*Cystophora cristata*), and ringed seal (*P. hispida*), were compared. Structural analyses were conducted to determine significant differences between FA of specific tissues among different seals and to analyze the existing differences in FA profiles of different species and tissues simultaneously.

MATERIALS AND METHODS

The blubber, muscle, brain, heart, liver, lung, and kidney of bearded (*E. barbatus*), gray (*H. grypus*), harbor (*P. vitulina*), harp (*P. groenlandica*), hooded (*C. cristata*), and ringed (*P. hispida*) seals were analyzed. Bearded, hooded, harp, and ringed seals were obtained from the northeast areas of Newfoundland by a Department of Fisheries and Oceans research vessel. Commercial fishermen on the south coast of Newfoundland and Nova Scotia obtained harbor and gray seals, respectively. All tissue samples were from adult specimens and were collected between April and June of 1995, 1996, and 1997. Upon retrieval and cleaning, samples were vacuum packaged, frozen, and stored at –26°C until analyzed.

Total lipids were extracted and quantified by the procedure of Bligh and Dyer (20). Prior to FA analysis, extracted lipids were converted to FAME by incubating with acidified methanol at 60°C for 15 h (19). Hydroquinone was added as an antioxidant, and methyl tricosanoate (23:0) was used as an internal standard. After subsequent extractions and washings with hexane and water, respectively, the fatty acid methyl esters (FAME) were dissolved in carbon disulfide.

FAME were analyzed using a Hewlett-Packard 5890 Series II chromatograph (Hewlett-Packard, Palo Alto, CA)

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with a SUPELCOWAX 10 column (0.25 mm diameter, 30 m length, 0.25 μm film thickness; Supelco Canada Ltd., Oakville, Ontario). A Hewlett-Packard 7673 autoinjector was used to inject the samples. The temperature of the oven was set at 220°C for 10.25 min followed by ramping to 240°C at 20°C/min, where it was held for 9 min. The injector temperature was at 270°C. Helium (15 mL/min) was used as a carrier gas. Hewlett-Packard 3365 Series II Chemstation software was used for data handling. The FAME were identified by comparison of their retention times with those of an authentic standard mixture (GLC-416; Nu-Chek-Prep, Elysian, MN) obtained under the same conditions.

All experiments were replicated three times, with a minimum of three individual seals and mean values ± SD reported for each sample type. An ANOVA and Tukey's Studentized range test (21) were used to determine significance of differences among means. Principal component analysis (PCA) was used to separate information from noise in several data matrices (22). PCA identifies a few linear correlations (principal components) that can be used to summarize the data, losing as little information in the process as possible. As a result, some degree of economy is achieved in that the variation in the original number of FA is accounted for by a smaller number of variables, two or three principal components. In this study, the PCA was used to produce two coordinates (principal components) that described the largest and second-largest variance among the samples.

RESULTS AND DISCUSSION

Lipid content. The lipid content of selected tissues of the six species of eastern Canadian phocid seals is provided in Table 1. As expected, the lipid content was highest in blubber followed by brain tissue. Muscle tissue had the lowest lipid content of all the tissues analyzed. The lipid content of liver was generally highest, whereas that of lung was generally lowest among tissues of kidney, heart, liver, and lung. There were significant ($P < 0.05$) differences between the same type of tissues for different seals, but none were consistently higher or lower. It should be noted that whereas blubber is primarily composed of TAG, organ lipids include both TAG and phospholipids. The FA composition of TAG in the organs may or may not be similar to that of the blubber of the same animal. However, our interest in this study was to establish a relationship between the FA of different tissues and species simultaneously. Differences between FA of TAG and phospholipids in different tissues would undoubtedly affect the overall FA profile, but their segregation into the two groups was not intended.

FA composition. The FA compositions of selected tissue lipids of the six species of eastern Canadian phocid seals are provided in Tables 2 to 8. In comparing similar tissues of different species one FA at a time, a univariate approach was employed. This approach showed significant ($P < 0.05$) differences among similar tissues from different seals. However, when comparing FA profiles of both different tissues and species using a multivariate approach, it was evident that differences were greater among different tissues than among the same tissues from different species.

(i) Blubber. Most of the previous studies on the composition of seal FA have focused on blubber lipids (4,6–8,11, 13–15,23,24). As shown in Table 2, in most species, 18:1n-9 was the predominant FA and was found in the highest proportion in the gray seal. In harbor and ringed seals 16:1n-7 was the predominant FA. Palmitoleic acid (16:1n-7) was the only FA present in significantly ($P < 0.05$) different proportions in all species. Significant differences ($P < 0.05$) in 12 FA were found in at least two species.

Generally, blubber lipids have a unique FA composition when compared to lipids of other tissues. The first notable feature of blubber lipids is a low concentration of 20:4n-6. Dimethyl acetals, the derivatives of 1-*O*-alk-1′-enyl linked ether chains, common to plasmalogens, were also noticeably absent or were present in only very small concentrations. This was expected as plasmalogens are commonly associated with polar lipids, and this fraction accounted for less than 1% of blubber lipids (16).

For blubber lipids of all species of seals, monounsaturated FA were the most predominant. Saturated FA were the least abundant group in all species except in the hooded seal. Hooded seal blubber lipids had the highest level of saturated FA and the lowest levels of PUFA. Ring seal blubber lipids, on the other hand, had the lowest level of saturated FA and the highest content of PUFA. Ring seal blubber lipids were also

TABLE 1
Lipid Content (g/100 g tissue) of Selected Tissues from Six Species of Seals[a]

Tissue	Harp	Gray	Harbor	Ringed	Hooded	Bearded[b]
Blubber	$93.88 \pm 1.64^{b,3}$	$91.93 \pm 1.07^{a,b,4}$	$92.72 \pm 1.13^{a,b,3}$	$93.55 \pm 1.98^{a,b,3}$	$89.43 \pm 1.82^{a,3}$	90.45
Muscle	$1.92 \pm 0.03^{a,1}$	$1.82 \pm 0.03^{a,1}$	$1.68 \pm 0.41^{a,1}$	$1.85 \pm 0.53^{a,1}$	$2.36 \pm 0.74^{a,1}$	1.74
Brain	$8.10 \pm 0.32^{a,b,2}$	$10.25 \pm 0.10^{c,3}$	$9.86 \pm 0.84^{b,c,2}$	$6.86 \pm 1.01^{a,2}$	$7.40 \pm 0.79^{a,2}$	12.58
Kidney	$2.97 \pm 0.18^{a,1}$	$3.42 \pm 0.04^{b,c,1,2}$	NA	$3.58 \pm 0.07^{c,1}$	$3.14 \pm 0.05^{a,b,1}$	3.05
Heart	$2.19 \pm 0.31^{a,1}$	$1.81 \pm 0.38^{a,1}$	$1.86 \pm 0.14^{a,1}$	$2.32 \pm 0.01^{a,1}$	$2.04 \pm 0.01^{a,1}$	1.70
Liver	$3.83 \pm 0.19^{a,b,1}$	$5.60 \pm 0.94^{b,2}$	NA	$3.71 \pm 0.07^{a,b,1}$	$3.66 \pm 0.03^{a,b,1}$	2.71
Lung	$2.24 \pm 0.46^{b,1}$	$2.04 \pm 0.03^{b,1}$	$1.88 \pm 0.02^{a,b,1}$	$2.05 \pm 0.02^{b,1}$	$1.76 \pm 0.01^{a,b,1}$	1.06

[a]Mean ± SD of three samples. The means followed by different alphabetical roman superscripts in each column are significantly different ($P < 0.05$) from each other. Similarly, the means followed by different numerical roman superscripts in each row are significantly different ($P < 0.05$) from each other. NA, sample was not available for analysis.
[b]Bearded seal was not included in statistical analysis because only one specimen was available for analysis.

TABLE 2
FA Composition (g/100 g) of Blubber of Various Species of Seal[a]

FA	Bearded[b]	Gray	Harbor	Harp	Hooded	Ringed
14:0	3.05	3.83 ± 0.03[a]	4.52 ± 0.13[b]	4.66 ± 0.49[b]	4.40 ± 0.38[a,b]	3.36 ± 0.66[a]
16:0 DMA	ND	ND	ND	ND	ND	ND
16:0	10.14	6.61 ± 0.08[a,b]	8.03 ± 0.38[b,c]	6.24 ± 0.44[a,b]	9.81 ± 1.57[c]	4.82 ± 2.07[a]
16:1n-7	17.77	12.77 ± 0.09[b]	19.26 ± 0.53[d]	14.93 ± 0.46[c]	10.09 ± 0.35[a]	23.12 ± 0.18[e]
18:0 DMA	ND	ND	ND	ND	ND	ND
18:1n-9 DMA	ND	ND	ND	ND	ND	ND
18:1n-7 DMA	ND	0.45 ± 0.01	ND	0.46 ± 0.00	ND	ND
18:0	2.15	0.94 ± 0.02[b]	0.85 ± 0.02[a,b]	0.95 ± 0.03[b]	1.83 ± 0.31[c]	0.42 ± 0.19[a]
18:1n-9	16.76	24.50 ± 0.44[c]	18.61 ± 0.55[a]	18.59 ± 1.01[a]	22.77 ± 2.66[b,c]	19.72 ± 1.33[a,b]
18:1n-7	9.49	4.95 ± 0.09[b]	5.16 ± 0.44[b]	3.57 ± 0.36[a]	3.75 ± 0.47[a]	5.03 ± 0.46[b]
18:2n-6	2.30	1.28 ± 0.00[a]	1.27 ± 0.04[a]	1.36 ± 0.20[a,b]	1.63 ± 0.20[b]	2.58 ± 0.02[c]
20:1n-9	5.08	12.50 ± 0.43[b]	9.06 ± 0.33[a,b]	12.56 ± 2.92[b]	13.00 ± 1.86[b]	6.71 ± 2.17[a]
20:4n-6	0.94	0.51 ± 0.00[a]	0.44 ± 0.00[a]	0.36 ± 0.96[a]	0.31 ± 0.03[a]	0.30 ± 0.02[a]
20:5n-3	8.28	4.85 ± 0.13[a]	9.31 ± 0.21[b]	6.82 ± 0.69[a,b]	5.21 ± 1.65[a]	8.72 ± 1.06[b]
22:0	0.63	2.26 ± 0.12[a,b]	1.19 ± 0.02[a]	3.61 ± 1.60[b,c]	5.53 ± 0.79[c]	0.75 ± 0.67[a]
22:1n-11	0.27	0.62 ± 0.03[a]	0.31 ± 0.01[a]	0.77 ± 0.61[a]	0.86 ± 0.33[a]	0.34 ± 0.01[a]
22:5n-3	4.26	5.06 ± 0.05[c,d]	4.22 ± 0.14[b]	4.78 ± 0.25[b,c]	2.29 ± 0.08[a]	5.46 ± 0.47[d]
22:6n-3	7.22	8.91 ± 0.29[a]	7.76 ± 0.98[a]	10.48 ± 1.98[a]	9.56 ± 2.36[a]	9.45 ± 1.74[a]

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another. DMA, dimethyl acetal. For other abbreviation see Table 1.
[b]Bearded seal was not included in the statistical analysis as only one specimen was available for analysis.

significantly ($P < 0.05$) higher in their content of n-3 PUFA than were the blubber lipids of several other species, whereas hooded seal blubber lipids tended to have a lower content of n-3 PUFA.

Seals are carnivorous mammals that originally evolved on land and eventually returned to the sea. Thus, their vital organs have a preference for n-6 FA such as arachidonic acid; these occur mainly in the phospholipid fraction of organ lipids. The blubber, however, is composed mainly of TAG, and its FA constituents are reassembled by the seals from dietary FA to address functional requirements of the species involved. For example, blubber may contain low amounts of 22:1 to ensure that the layer next to the skin is always liquid and in times of lactation resist hydrolysis when 16:0 and other FA are urgently needed for transfer to pups.

(ii) Muscle. FA were significantly ($P < 0.05$) different between at least two species, but none were different in all six species. Harbor and ringed seal muscle lipids were significantly ($P < 0.05$) higher in their content of eicosapentaenoic acid (EPA) (20:5n-3) than were those of the remaining species (see Table 3).

TABLE 3
FA Composition (g/100 g) of Muscle Lipids of Various Species of Seal

FA	Bearded	Gray	Harbor	Harp	Hooded	Ringed
14:0	2.44	2.15 ± 0.05[a]	1.88 ± 0.50[a]	2.46 ± 0.71[a]	3.90 ± 0.35[a]	2.71 ± 2.05[a]
16:0 DMA	1.63	1.99 ± 0.08[b]	1.50 ± 0.16[a,b]	1.86 ± 0.15[b]	0.35 ± 0.29[a]	2.08 ± 1.03[b]
16:0	13.62	13.79 ± 0.73[a]	14.02 ± 1.10[a]	12.29 ± 0.91[a]	12.69 ± 2.38[a]	16.20 ± 2.49[a]
16:1n-7	11.06	3.73 ± 0.40[a]	5.82 ± 0.34[a]	7.30 ± 0.79[a]	5.27 ± 1.21[a]	5.34 ± 3.01[a]
18:0 DMA	0.54	0.97 ± 0.07[b]	0.80 ± 0.56[a,b]	0.78 ± 0.08[a,b]	0.21 ± 0.03[a]	0.57 ± 0.27[a,b]
18:1n-9 DMA	0.61	0.84 ± 0.05[b,c]	1.13 ± 0.03[c]	0.84 ± 0.09[b,c]	0.25 ± 0.28[a]	0.70 ± 0.06[b]
18:1n-7 DMA	1.19	1.14 ± 0.04[b]	0.75 ± 0.53[a,b]	0.97 ± 0.11[b]	0.10 ± 0.11[a]	0.73 ± 0.35[a,b]
18:0	5.65	6.20 ± 0.20[a,b]	12.29 ± 5.57[b]	5.93 ± 0.19[a,b]	4.84 ± 0.78[a]	6.22 ± 2.36[a,b]
18:1n-9	17.08	17.48 ± 0.48[b]	12.73 ± 1.61[a]	18.48 ± 0.68[b]	19.84 ± 0.23[b]	18.14 ± 1.68[b]
18:1n-7	7.70	3.57 ± 0.13[a]	4.71 ± 0.58[a]	4.88 ± 1.39[a]	3.41 ± 0.46[a]	3.71 ± 0.43[a]
18:2n-6	3.01	1.98 ± 0.05[b]	2.00 ± 0.18[b]	1.54 ± 0.12[a]	1.91 ± 0.08[b]	2.76 ± 0.14[c]
20:1n-9	5.03	11.63 ± 0.28[b]	4.65 ± 1.33[a]	11.75 ± 1.58[b]	14.51 ± 2.03[b]	6.35 ± 2.39[a]
20:4n-6	5.10	4.31 ± 0.09[a,b]	7.11 ± 2.29[b]	3.87 ± 0.63[a,b]	1.97 ± 0.66[a]	4.26 ± 2.06[a,b]
20:5n-3	6.10	5.60 ± 0.14[a]	10.46 ± 1.23[b]	5.56 ± 0.60[a]	4.57 ± 0.12[a]	9.21 ± 1.60[b]
22:0	1.10	4.46 ± 0.13[b]	1.44 ± 0.06[a]	4.46 ± 0.78[b]	6.82 ± 0.73[c]	2.02 ± 0.99[a]
22:1n-11	ND	0.62 ± 0.02[b]	0.29 ± 0.01[a]	0.93 ± 0.23[c]	ND	0.08 ± 0.00[a]
22:5n-3	3.58	2.94 ± 0.25[b]	2.12 ± 0.06[a]	2.21 ± 0.32[a]	1.79 ± 0.16[a]	2.31 ± 0.08[a]
22:6n-3	8.55	9.30 ± 0.82[a]	10.02 ± 2.12[a]	6.73 ± 1.30[a]	8.52 ± 0.91[a]	9.49 ± 0.45[a]

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another. For abbreviations see Tables 1 and 2.
[b]Bearded seal was not included in the statistical analysis as only one specimen was available for analysis.

TABLE 4
FA Composition (g/100 g lipid) of Brain Lipids of Various Species of Seal[a]

FA	Bearded	Gray	Harbor	Harp	Hooded	Ringed
14:0	0.28	0.31 ± 0.00[a]	0.62 ± 0.20[b]	0.48 ± 0.07[a,b]	0.48 ± 0.12[a,b]	0.45 ± 0.03[a,b]
16:0 DMA	1.62	2.05 ± 0.12[c]	1.95 ± 0.01[b,c]	1.66 ± 0.19[a,b]	1.38 ± 0.15[a]	1.53 ± 0.15[a]
16:0	11.98	13.96 ± 0.52[a]	14.74 ± 0.77[a]	15.45 ± 0.64[a]	15.48 ± 1.16[a]	18.18 ± 0.75[b]
16:1n-7	0.86	0.94 ± 0.02[a]	1.15 ± 0.13[a,b]	1.33 ± 0.22[b]	1.07 ± 0.07[a,b]	1.28 ± 0.16[a,b]
18:0 DMA	2.29	3.00 ± 0.18[a]	4.01 ± 0.04[b,c]	4.38 ± 0.43[c]	3.35 ± 0.20[a,b]	2.91 ± 0.26[a]
18:1n-9 DMA	1.72	1.84 ± 0.11[c]	1.96 ± 0.00[c]	1.82 ± 0.08[c]	1.18 ± 0.08[b]	0.84 ± 0.07[a]
18:1n-7 DMA	3.51	4.01 ± 0.22[c]	2.89 ± 0.04[b]	2.69 ± 0.18[b]	1.73 ± 0.11[a]	1.95 ± 0.21[a]
18:0	14.30	16.33 ± 0.56[a]	19.22 ± 0.87[b]	18.08 ± 0.69[b]	18.06 ± 0.23[b]	19.08 ± 0.64[b]
18:1n-9	15.91	17.25 ± 0.61[b]	14.86 ± 1.47[a,b]	14.02 ± 0.89[a]	13.48 ± 1.14[a]	12.89 ± 0.47[a]
18:1n-7	4.25	4.86 ± 0.16[a]	4.92 ± 0.84[a]	4.60 ± 0.28[a]	4.64 ± 0.06[a]	5.59 ± 0.18[a]
18:2n-6	ND	0.12 ± 0.00[a]	ND	0.15 ± 0.09[a]	0.28 ± 0.12[a]	0.32 ± 0.14[a]
20:1n-9	3.33	2.09 ± 0.10[c]	1.72 ± 0.58[b,c]	1.83 ± 0.24[c]	0.12 ± 0.21[a]	0.78 ± 0.45[a,b]
20:4n-6	7.58	5.51 ± 0.04[a]	5.03 ± 0.57[a]	5.29 ± 0.22[a]	6.92 ± 0.99[b]	5.99 ± 0.30[a,b]
20:5n-3	0.25	0.34 ± 0.00[a]	0.57 ± 0.74[a]	0.70 ± 0.60[a]	1.02 ± 0.06[a]	0.94 ± 0.04[a]
22:0	0.58	ND	ND	0.25 ± 0.09[a]	0.44 ± 0.02[b]	0.28 ± 0.00[a]
22:1n-11	ND	0.19 ± 0.01[a]	0.27 ± 0.13[a]	0.21 ± 0.13[a]	ND	ND
22:5n-3	0.57	3.25 ± 0.10[b]	3.18 ± 0.05[b]	2.92 ± 0.26[b]	1.66 ± 0.07[a]	1.95 ± 0.10[a]
22:6n-3	13.51	13.31 ± 0.45[a]	14.07 ± 1.39[a,b]	15.56 ± 0.64[b,c]	14.49 ± 0.54[a,b,c]	16.33 ± 0.83[c]

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another. For abbreviations see Tables 1 and 2.
[b]Bearded seal was not included in the statistical analysis as only one specimen was available for analysis.

The predominant FA in lipids of muscle tissues of all species, except the harbor seal, was 18:1n-9. In the harbor seal 16:0 was the predominant FA. However, even in harbor seal muscle lipids, the total amount of 18:1 (n-9 and n-7) fraction was larger than that of 16:0. The 20:4n-6 content of muscle lipids (1.97–7.11%) was much higher than that in blubber lipids (0.30-0.51%). Similar results have been reported in previous studies on muscle tissues of both the harp seal (15) and Mediterranean monk seal (16). These findings suggest that the majority of the FA present in blubber lipids are those that have been absorbed from the diet and transported directly in chylomicrons to blubber without modification. However, the FA of the lipids from muscles and other tissues are probably modified by the liver before being deposited. As a result, the FA composition of blubber lipids is similar to the FA composition of the lipids in the animals' diet and may also explain some of the variations in FA composition with season, species, geographic location, and age. Similarly, this explains why the FA compositions of the muscle and especially internal organs have a stronger resemblance to the FA compositions of similar tissues from terrestrial mammals (12).

Muscle lipids of all species also contained measurable

TABLE 5
FA Composition (g/100 g lipid) of Kidney Lipids of Various Species of Seal[a]

FA	Bearded	Gray	Harp	Hooded	Ringed
14:0	1.86 ± 0.10[a,b]	2.11 ± 0.01[a,b]	1.15 ± 0.88[a]	2.24 ± 0.16[b]	2.39 ± 0.10[b]
16:0 DMA	2.17 ± 0.01[a]	1.82 ± 0.08[a]	3.09 ± 0.67[b]	2.09 ± 0.20[a]	1.87 ± 0.01[a]
16:0	14.50 ± 0.37[b]	14.28 ± 0.09[a,b]	12.71 ± 0.19[a]	15.24 ± 1.28[b]	14.64 ± 0.37[b]
16:1n-7	6.54 ± 0.22[c]	5.00 ± 0.05[b]	4.05 ± 0.09[a]	4.60 ± 0.20[b]	7.05 ± 0.22[d]
18:0 DMA	1.02 ± 0.00[b]	0.56 ± 0.02[a]	1.65 ± 0.28[c]	1.07 ± 0.13[b]	0.83 ± 0.00[a,b]
18:1n-9 DMA	ND	0.57 ± 0.03[b]	0.74 ± 0.06[c]	0.48 ± 0.01[a]	0.69 ± 0.00[c]
18:1n-7 DMA	0.97 ± 0.01[d]	0.78 ± 0.03[c]	0.79 ± 0.07[c]	0.42 ± 0.02[a]	0.59 ± 0.01[b]
18:0	12.29 ± 0.06[b]	10.36 ± 0.08[a]	12.30 ± 0.59[b]	15.91 ± 1.20[c]	11.13 ± 0.06[a,b]
18:1n-9	14.18 ± 0.25[b]	15.57 ± 0.31[c]	12.52 ± 0.45[a]	15.65 ± 0.81[c]	15.97 ± 0.25[c]
18:1n-7	6.96 ± 0.08[b]	6.73 ± 0.09[b]	5.50 ± 0.35[a]	5.65 ± 0.33[a]	6.07 ± 0.08[a]
18:2n-6	3.95 ± 0.09[d]	3.56 ± 0.06[c]	3.33 ± 0.03[b]	3.06 ± 0.01[a]	3.42 ± 0.09[b,c]
20:1n-9	2.26 ± 0.03[a]	4.33 ± 0.77[b]	2.20 ± 0.57[a]	3.80 ± 1.03[a,b]	2.79 ± 0.03[a,b]
20:4n-6	11.86 ± 0.18[c]	10.55 ± 0.21[b,c]	10.11 ± 1.08[b]	6.72 ± 0.71[a]	7.95 ± 0.18[a]
20:5n-3	10.81 ± 0.33[b]	5.93 ± 0.47[a]	9.86 ± 0.53[b]	11.10 ± 1.75[b]	10.31 ± 0.33[b]
22:0	0.94 ± 0.08[a]	0.84 ± 0.25[a]	0.99 ± 0.67[a]	1.06 ± 0.08[a]	0.69 ± 0.08[a]
22:1n-11	ND	0.83 ± 0.40[b]	0.21 ± 0.04[a]	0.72 ± 0.01[a,b]	0.64 ± 0.01[a,b]
22:5n-3	1.26 ± 0.04[b]	2.24 ± 0.03[c]	2.13 ± 0.05[c]	0.51 ± 0.11[a]	2.18 ± 0.04[c]
22:6n-3	6.61 ± 0.01[b,c]	4.76 ± 1.22[a,b]	3.29 ± 0.83[a]	6.51 ± 0.48[b,c]	7.23 ± 0.01[c]

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another. For abbreviations see Tables 1 and 2.

TABLE 6
FA Composition (g/100 g lipid) of Heart Lipids of Various Species of Seal[a]

FA	Bearded	Gray	Harbor	Harp	Hooded	Ringed
14:0	1.86 ± 0.09^{d}	1.14 ± 0.01^{b}	1.72 ± 0.12^{c,d}	0.91 ± 0.03^{a}	1.68 ± 0.04^{c}	1.21 ± 0.01^{b}
16:0 DMA	1.97 ± 0.06^{a}	2.92 ± 0.06^{c}	2.77 ± 0.09^{c}	3.74 ± 0.10^{d}	2.57 ± 0.03^{b}	3.96 ± 0.07^{e}
16:0	12.85 ± 0.61^{c}	11.01 ± 0.04^{a,b}	10.49 ± 0.43^{a}	10.56 ± 0.81^{a}	12.45 ± 0.13^{c}	12.04 ± 0.06^{b,c}
16:1n-7	12.73 ± 0.42^{e}	3.50 ± 0.05^{a}	6.21 ± 0.24^{d}	4.32 ± 0.12^{b}	5.18 ± 0.15^{c}	5.18 ± 0.11^{c}
18:0 DMA	0.78 ± 0.01^{a}	1.32 ± 0.02^{b,c}	1.62 ± 0.08^{c}	2.69 ± 0.33^{d}	1.33 ± 0.00^{b,c}	1.15 ± 0.10^{a,b}
18:1n-9 DMA	0.72 ± 0.02^{a}	1.66 ± 0.04^{b}	1.79 ± 0.04^{c}	2.58 ± 0.05^{d}	1.62 ± 0.05^{b}	1.57 ± 0.01^{b}
18:1n-7 DMA	1.35 ± 0.01^{b}	1.43 ± 0.03^{c}	1.47 ± 0.05^{c}	1.74 ± 0.03^{d}	0.79 ± 0.02^{a}	1.38 ± 0.01^{b,c}
18:0	7.63 ± 0.09^{a}	9.07 ± 0.04^{b}	10.55 ± 0.21^{c}	11.09 ± 0.34^{d}	10.49 ± 0.01^{c}	11.61 ± 0.06^{e}
18:1n-9	16.49 ± 0.22^{b}	17.46 ± 0.24^{c}	14.62 ± 0.36^{a}	16.69 ± 0.17^{b}	19.81 ± 0.40^{d}	15.31 ± 0.00^{a}
18:1n-7	9.41 ± 0.04^{d}	4.01 ± 0.04^{a}	4.14 ± 0.10^{a}	4.56 ± 0.25^{b,c}	4.81 ± 0.08^{c}	4.26 ± 0.03^{b}
18:2n-6	3.40 ± 0.07^{b}	3.68 ± 0.08^{c}	2.80 ± 0.07^{a}	3.86 ± 0.08^{c}	3.45 ± 0.08^{b}	5.20 ± 0.01^{d}
20:1n-9	3.88 ± 0.02^{a}	3.76 ± 0.38^{a}	3.88 ± 0.09^{a}	4.51 ± 0.05^{b}	9.00 ± 0.10^{c}	4.89 ± 0.12^{b}
20:4n-6	9.27 ± 0.15^{c}	11.04 ± 0.20^{e}	5.65 ± 0.24^{a}	9.90 ± 0.13^{d}	5.73 ± 0.17^{a}	7.98 ± 0.05^{b}
20:5n-3	8.08 ± 0.11^{b}	6.92 ± 0.06^{a}	11.40 ± 0.31^{d}	9.74 ± 0.13^{c}	11.79 ± 0.40^{d}	12.80 ± 0.13^{e}
22:0	ND	1.72 ± 0.04^{b}	0.82 ± 0.18^{a}	0.58 ± 0.32^{a}	ND	ND
22:1n-11	0.79 ± 0.00^{c}	0.37 ± 0.01^{b}	0.18 ± 0.03^{a}	ND	2.44 ± 0.08^{d}	ND
22:5n-3	2.35 ± 0.08^{c}	1.62 ± 0.03^{b}	2.42 ± 0.04^{c}	1.17 ± 0.06^{a}	1.16 ± 0.00^{a}	1.57 ± 0.00^{b}
22:6n-3	5.57 ± 0.06^{b}	6.08 ± 0.85^{b}	10.40 ± 0.42^{c}	4.11 ± 0.59^{a}	5.87 ± 0.11^{b}	5.29 ± 0.06^{a,b}

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another. For abbreviations see Tables 1 and 2.

amounts of dimethyl acetals. These are formed when the alkenyl linkage in plasmalogens is cleaved with acidified methanol during transmethylation. Plasmalogens are primarily found in membrane phospholipids and, apart from the general structural function of all membrane phospholipids, no specific function has been attributed to them. The ether glycerophospholipids tend to be rich in PUFA, which does suggest a role as a storage reservoir for these FA. This may be due to the apparently protective nature of the ether bond against hydrolysis of the acyl group at the *sn*-2 position by phospholipase A_2 (25).

(iii) Brain. The FA composition of brain lipids for the six species of eastern Canadian phocid seals is provided in Table 4. The predominant FA was 18:0 for harbor, harp, hooded, and ringed seal brain lipids, whereas it was 18:1n-9 in the brain lipids of bearded and gray seals.

The FA composition of brain tissue lipids of all species was unique when compared to all other tissues. The first notable feature was the high dimethyl acetal content (>7%). This was probably due to very high polar lipid (~70%) and very low TAG contents (<1%) (Durnford, E., and F. Shahidi, unpublished data). The proportion of EPA (20:5n-3) in total

TABLE 7
FA Composition (g/100 g lipid) of Lung Lipids of Various Species of Seal[a]

FA	Bearded	Gray	Harbor	Harp	Hooded	Ringed
14:0	1.89 ± 0.05^{a}	1.75 ± 0.01^{a}	4.02 ± 0.01^{d}	2.40 ± 0.06^{b}	2.52 ± 0.16^{b,c}	2.65 ± 0.06^{c}
16:0 DMA	1.38 ± 0.00^{a}	1.52 ± 0.02^{a,b}	1.57 ± 0.02^{a,b}	1.93 ± 0.02^{c}	1.77 ± 0.26^{b,c}	1.59 ± 0.12^{a,b}
16:0	24.12 ± 0.01^{a}	25.55 ± 0.13^{a,b}	24.59 ± 0.22^{a,b}	24.45 ± 0.67^{a,b}	28.37 ± 1.70^{c}	26.53 ± 0.57^{b,c}
16:1n-7	6.86 ± 0.17^{e}	2.41 ± 0.03^{a}	4.54 ± 0.00^{c}	2.54 ± 0.08^{a}	3.64 ± 0.19^{b}	6.17 ± 0.13^{d}
18:0 DMA	ND	1.09 ± 0.13^{b}	1.22 ± 0.05^{b}	1.68 ± 0.08^{c}	0.80 ± 0.13^{a}	0.77 ± 0.04^{a}
18:1n-9 DMA	ND	0.72 ± 0.02^{b}	0.64 ± 0.04^{a}	0.92 ± 0.02^{c}	0.61 ± 0.00^{a}	ND
18:1n-7 DMA	ND	0.85 ± 0.01^{b}	0.94 ± 0.03^{c}	1.01 ± 0.00^{d}	0.47 ± 0.00^{a}	0.82 ± 0.03^{b}
18:0	11.74 ± 0.08^{c}	8.65 ± 0.05^{a}	8.78 ± 0.04^{a}	8.72 ± 0.26^{a}	10.10 ± 0.54^{b}	8.71 ± 0.23^{a}
18:1n-9	14.05 ± 0.11^{c}	12.87 ± 0.08^{b}	11.13 ± 0.05^{a}	13.41 ± 0.28^{b,c}	15.48 ± 0.87^{d}	14.30 ± 0.19^{c}
18:1n-7	8.17 ± 0.04^{c}	4.43 ± 0.02^{b}	3.92 ± 0.01^{a}	3.96 ± 0.27^{a}	3.95 ± 0.26^{a}	9.41 ± 0.03^{d}
18:2n-6	ND	1.54 ± 0.21^{c}	0.94 ± 0.06^{a}	1.14 ± 0.02^{a,b}	1.28 ± 0.02^{b,c}	2.03 ± 0.11^{d}
20:1n-9	ND	3.72 ± 0.78^{b,c}	2.74 ± 0.02^{a,b}	2.68 ± 0.62^{a,b}	4.80 ± 0.25^{c}	2.20 ± 0.18^{a}
20:4n-6	11.35 ± 0.30^{c}	6.06 ± 0.07^{b}	3.78 ± 0.01^{a}	5.81 ± 0.14^{b}	4.23 ± 0.13^{a}	6.22 ± 0.21^{b}
20:5n-3	9.66 ± 0.45^{c}	5.56 ± 0.08^{a}	8.12 ± 0.03^{b}	4.86 ± 0.31^{a}	8.28 ± 0.42^{b}	8.75 ± 0.14^{b}
22:0	ND	0.42 ± 0.00^{a}	ND	0.56 ± 0.27^{a}	ND	0.56 ± 0.09^{a}
22:1n-11	ND	1.08 ± 0.02^{c}	0.62 ± 0.01^{a}	0.81 ± 0.00^{b}	1.32 ± 0.04^{d}	ND
22:5n-3	ND	3.17 ± 0.05^{c}	3.56 ± 0.02^{d}	2.35 ± 0.04^{b}	1.71 ± 0.00^{a}	4.53 ± 0.06^{e}
22:6n-3	8.71 ± 0.06^{c}	6.75 ± 0.04^{a,b}	9.05 ± 0.02^{c}	5.80 ± 1.07^{a}	7.96 ± 0.23^{b,c}	6.36 ± 0.12^{a}

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another. For abbreviations see Tables 1 and 2.

TABLE 8
FA Composition (g/100/g lipid) of Liver Lipids of Various Species of Seal[a]

FA	Bearded	Gray	Harp	Hooded	Ringed
14:0	0.95 ± 0.01[a]	1.34 ± 0.04[b,c]	1.21 ± 0.20[b]	1.63 ± 0.00[c]	1.30 ± 0.00[b,c]
16:0 DMA	ND	0.14 ± 0.00[a]	0.15 ± 0.01[a]	ND	ND
16:0	13.37 ± 0.14[a]	16.08 ± 0.55[b]	13.63 ± 0.76[a]	12.64 ± 0.01[a]	21.02 ± 0.06[c]
16:1n-7	6.07 ± 0.04[d]	2.94 ± 0.06[a]	5.34 ± 0.13[c]	5.09 ± 0.06[b]	6.28 ± 0.02[e]
18:0 DMA	ND	ND	0.16 ± 0.04	ND	ND
18:1n-9 DMA	ND	ND	0.19 ± 0.06	ND	ND
18:1n-7 DMA	ND	ND	0.13 ± 0.04	ND	ND
18:0	17.27 ± 0.18[c]	14.94 ± 0.51[b]	19.55 ± 0.87[d]	18.03 ± 0.16[c]	13.07 ± 0.01[a]
18:1n-9	9.91 ± 0.12[a]	12.79 ± 0.40[b,c]	11.80 ± 1.45[b]	15.09 ± 0.04[d]	14.39 ± 0.07[c,d]
18:1n-7	10.29 ± 0.14[b]	5.39 ± 0.14[a]	6.10 ± 0.84[a]	6.05 ± 0.11[a]	9.41 ± 0.06[b]
18:2n-6	2.11 ± 0.04[a]	2.61 ± 0.06[b]	2.04 ± 0.38[a]	2.29 ± 0.02[a,b]	2.03 ± 0.01[a]
20:1n-9	2.80 ± 0.02[a,b]	3.25 ± 0.02[b]	3.40 ± 0.58[b]	7.06 ± 0.04[c]	2.20 ± 0.05[a]
20:4n-6	11.47 ± 0.10[c]	9.28 ± 0.30[b]	9.50 ± 0.57[b]	5.64 ± 0.20[a]	6.22 ± 0.03[a]
20:5n-3	11.66 ± 0.08[b]	9.24 ± 0.33[a]	8.07 ± 1.74[a]	11.86 ± 0.59[b]	8.75 ± 0.20[a]
22:0	ND	0.96 ± 0.11[b]	0.58 ± 0.04[a]	ND	0.56 ± 0.01[a]
22:1n-11	ND	0.19 ± 0.13[a]	0.23 ± 0.13[a]	0.96 ± 0.08[b]	ND
22:5n-3	2.82 ± 0.06[c]	4.11 ± 0.12[d]	2.16 ± 0.05[b]	1.64 ± 0.13[a]	4.53 ± 0.02[e]
22:6n-3	7.67 ± 0.08[a,b]	6.69 ± 0.44[a,b]	8.17 ± 1.83[a,b]	8.89 ± 0.41[b]	6.36 ± 0.08[a]

[a]Mean ± SD of three samples. The means followed by different superscripts are significantly ($P < 0.05$) different from one another.

lipids was very low, whereas that of docosahexaenoic acid (DHA) (22:6n-3) was the highest in all tissues analyzed. The high DHA content was expected, as both brain and retina lipids are known to be rich in DHA. In brain lipids, the content of the saturated FA 14:0 was relatively low, whereas that of 18:0 was relatively high.

Ringed seal brain lipids had significantly ($P < 0.05$) higher levels of DHA than those of gray and harbor seals. However, for the most part, there were fewer species-to-species differences in brain tissue lipids than in the lipids of tissues previously discussed. That the FA composition of lipids in the brains of different species is strongly conserved may be due to the functional roles of individual FA in brain lipids. In many tissues, especially blubber, the lipids present are often used as an energy reserve; however, brain tissue does not utilize lipids as an energy source, so their presence in the brain is most likely structural and functional in nature. Another factor that may result in the strong conservation of FA composition is that there may be requirements for specific lipid classes, e.g., cerebrosides, and these classes may have specific FA compositions (e.g., sphingomyelin generally has a high content of 16:0) (26).

(iv) Kidney. The FA composition of kidney lipids of different seal species is provided in Table 5. The FA 16:1n-7 and 18:1n-7 dimethyl acetals were most significantly ($P < 0.05$) different from species to species. The predominant FA was 18:1n-9 in bearded, gray, and ringed seal kidney lipids. However, in the harp seal 16:0 was the predominant FA, and 18:0 was predominant in the hooded seal. The content of 20:4n-6 was higher in kidney lipids than in the lipids of blubber, muscle, and brain tissues. In all species, 20:5n-3 was the dominant n-3 PUFA. The dimethyl acetal content in FA in kidney ranged from 3.73 to 6.27%. Similar trends were reported in a previous study (13), except that dimethyl acetals were not reported and the contents of 20:4 and 20:5 were much lower than those found in this study.

(v) Heart. Table 6 summarizes the FA composition of heart lipids of seals of eastern Canada. The FA 16:1n-7, 18:0, 20:4n-6, and 20:5n-3 were found to be significantly ($P < 0.05$) different for most species. In all species, 18:1n-9 was the dominant FA. Similar to other internal organ lipids, heart lipids had a relatively high content of 20:4n-6. The FA 20:5n-3 was the predominant n-3 PUFA in heart lipids of all species. The dimethyl acetal content of heart lipids ranged from 4.82 to 10.75%.

The content of 18:2n-6 was higher in heart tissue lipids than in the lipids of others tissues. This was most likely due to a somewhat higher cardiolipin content in heart tissue derived from a high level of mitochondria. In fact, cardiolipin in adult rat is composed of approximately 75% 18:2n-6. Since cardiolipin is almost exclusively located in the inner mitochondrial membrane, it is most likely that this particular membrane has a very specific composition with respect to both the polar headgroup and the FA composition of its lipids, thus conferring specific properties important to the performance of its functions (25).

Several studies have reported the FA composition of heart lipids of various seal species. A study on one harbor seal (7) reported the FA composition of the TAG and phospholipid fractions, as did a later study on two harbor seals and a gray seal (8). The general trends outlined above appear to be consistent with these studies. A study of a large number of harp, hooded, and harbor seals, using chemometric methods of FA analysis, has also provided FA compositions of heart lipids (18). Again the general trends were similar, but they did report much higher values for the contents of 18:0, 18:1n-9, 18:2n-6; the presence and amount of 22:5n-3 were not reported. None of these studies included data for dimethyl acetals. However, a study on the FA composition of the Mediterranean monk seal (16) reported dimethyl acetal values.

(vi) Lung. The FA composition of lung lipids is given in Table 7. The unique feature of the FA composition of lung lipids is the very high content of 16:0 (24.12–28.37%). This

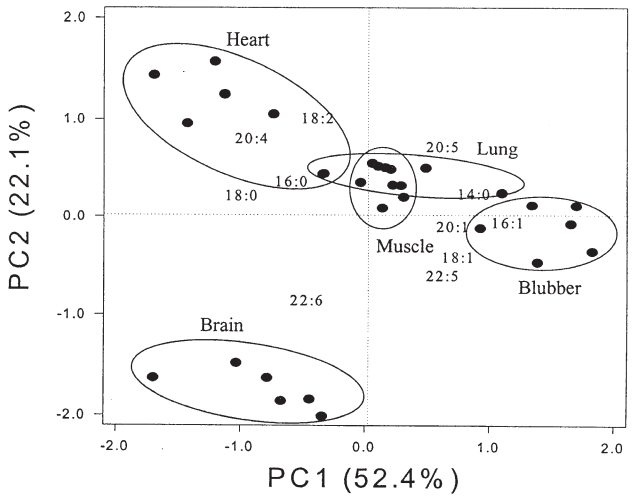

FIG. 1. A plot of a principal component (PC) analysis of the FA compositions of selected tissues of bearded, gray, harbor, harp, hooded, and ringed seals.

FA was predominant in lung lipids of all seal species analyzed. The contents of 20:5n-3 and 22:6n-3 were very similar, with 20:5n-3 being the most abundant n-3 PUFA in bearded, hooded, and ringed seals and 22:6n-3 being the most abundant n-3 PUFA in gray, harbor, and harp seals. The dimethyl acetal content of lung lipids ranged from 1.38 to 5.54%, and 22:5n-3 was found to vary significantly ($P < 0.05$) from species to species.

The very high content of palmitic acid (16:0) in lung tissue lipids is most likely due to a high proportion of dipalmitoylphosphatidylcholine (DPPC) from pulmonary surfactant lipids. Palmitic acid is known to be a major FA present in lung PC and the saturated PC are predominant in DPPC, which accounts for approximately half of the total surfactant lipids (27). It is also generally agreed that DPPC is the major functional agent of lung surfactant due to its surface-active properties. The presence of rigid acyl chains in the molecule under physiological conditions is linked to these properties (27).

(vii) Liver. The FA composition of the liver lipids of different seal species is provided in Table 8. The 16:1n-7 content varied significantly ($P < 0.05$) among species analyzed. The predominant FA was 18:0 for bearded, harp, and hooded seals, whereas 16:0 was the dominant FA in the livers of gray and ringed seals. A notable feature of the liver lipids was the absence or very low concentration of dimethyl acetals. As with other internal organ lipids, the content of 20:4n-6 was fairly high. The FA 20:5n-3 was the predominant n-3 PUFA present, except in the harp seal where 22:6n-3 was found in greater abundance.

Comparison of tissues and species. To this point, the individual FA of different species of seals have been compared by considering one tissue at a time. This has allowed for the identification of any differences among species and some unique features of several tissues. However, much more information may be deduced by comparing FA compositions across species and tissues simultaneously. This was accomplished using a multivariate approach.

The multivariate approach employed was a PCA. The PCA identifies linear correlations (principal components) that can be used to summarize the data while losing as little information in the process as possible. In this study, the PCA was used to produce two coordinates describing the largest and the second-largest variance among the samples from 11 of the most abundant FA. The first two principal components accounted for 74.5% of the variance in the samples. A PCA plot comparing the FA compositions of the lipids of blubber, brain, heart, lung, and muscle of the six eastern Canadian phocid seals is shown in Figure 1.

Figure 1 clearly demonstrates that the greatest differences existed from tissue to tissue and that brain tissue lipids were unique in their FA composition. This figure also allows conclusions to be drawn about the likely FA composition of a specific sample based on where that sample lies in relation to others in the plot. For example, the FA 22:6 tends to pull samples down along the second principal component (PC2) axis. As a result, samples high in 22:6 will be pulled in that direction. The FA 20:5 is high up on the PC2 axis and will pull samples high in 20:5 up and allow samples that are low in 20:5, such as brain lipids, to be pulled down even further. The FA 18:2 also causes samples high in it to fall high along the PC2, whereas 18:1 and 22:5 have more of a downward impact. Along the PC1 axis, the FA 20:4, 18:0, 16:0, and 18:2 pull to the left and 14:0, 22:5, 16:1, and 20:1 pull to the right.

Figure 1 shows that brain tissue lipids tend to be relatively high in 22:6 and 22:5 and low in 20:5 and 18:2. For blubber lipids we would conclude that they tend to be relatively high in 14:0, 22:5, 16:1, 18:1, and 20:1 and low in 20:4, 18:2, and 18:0. Heart tissue lipids tend to be high in 20:4 and 18:2 and low in 22:5 and 14:0. Since lung and muscle lie in the center of the plot, they would tend to have intermediate values for the outlying FA and higher values for the more centralized FA such as 16:0.

The different compositions of lipids found in the individual tissues are not just accidents of evolution but have evolved, in many cases, because of some specific benefits to the membrane in which they are found. The FA composition is known to be a determining factor in membrane fluidity, since shorter chain lengths and *cis* double bonds enhance liquidity and mobility. The degree of unsaturation in the FA of phospholipids has also been shown to affect cell permeability, osmotic fragility and cholesterol efflux in the outer monolayer of erythrocytes (28).

The results of this work demonstrate that FA compositions depend on both tissue and species of seal. Differences between species were less evident and clear trends were not apparent. Significant differences were generally limited to a small number of FA and were probably due to differences in dietary lipids rather than to special functional requirement for a specific species of seal. Among tissues, however, differences in FA compositions were much more apparent. Several FA found in a particular tissue were either much higher or lower across all species. These differences are most likely due to functional requirements of those FA in particular tissues. Since tissue lipids contain both TAG and phospholipids, the

existing differences may originate from their varying proportions in different tissues. However, blubber remains the only viable source of oil among different tissues in seals, and that is constituted primarily of TAG.

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[Received December 3, 2001; accepted June 20, 2002]