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Fatty Acids of Marine Algae from the Pacific Coast of North California

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Nineteen species of marine macrophytic algae collected in Bodega Bay, California were investigated for their fatty acid composition. Red, brown and green algae have distinguishing fatty acid profiles, which have a chemotaxonomic significance for seaweeds. This does not depend on the geographical location of the algae. Algal habitat conditions affect quantitative characteristics of the fatty acids. The content of polyunsaturated fatty acids in algae from California was found to be noticeably higher for most of the algal species examined in comparison with the same or related species from other regions.

Introduction

Marine algae comprising a few thousands of species (South and Whittick 1987) represent a considerable part of the littoral biomass. Many algal species have long been used as human food, animal fodder and source of valuable substances (Chapman and Chapman 1980). In addition, algal constituents are of interest from a pharmaceutical point of view (Radwan 1991). Marine algae are rich in polyunsaturated fatty acids (PUFAs) (Wood 1988, Kayama *et al.* 1989) and are of potential value as sources of essential fatty acids, important in the nutrition of humans and animals (Floreto *et al.* 1996, Newton 1996). However, up to now, only a limited number of algal species collected from a few sites in the World Ocean have been investigated for their fatty acid (FA) composition. Each phylum of marine macrophytic algae has its characteristic fatty acid pattern (Jamieson and Reid 1972, Khotimchenko and Svetashev 1987, Dembitsky 1996). Yet, there are discrepancies in the literature on the FA composition even for the same or related algal species, e. g. for *Laminaria* and *Undaria* species (Vaskovsky *et al.* 1996, Khotimchenko 1998), and for members of the genus *Gracilaria* (Araki *et al.* 1990, Khotimchenko *et al.* 1991). Some authors have suggested that the differences observed in the fatty acid composition of algae may be related to the varying geographical origins of the samples, or to the environmental factors under which the samples were obtained. This has affected comparisons between algae from different parts of the world (Stefanov *et al.* 1988, Aknin *et al.* 1990, Dembitsky *et al.* 1991). Therefore, we studied the fatty acid compositions of 19 of the most abundant red, brown and green algal species collected from Bodega Bay on the coast of California to verify chemo-taxonomic trends in FA distribution for marine algae and to examine the possible influence of habitat on their fatty acid composition.

The coast of California is rich in seaweeds both in biomass and algal species (Abbott and Hollenberg 1976), but we found no data on the fatty acids of algae from this area, except one report on the red alga *Porphyra perforata* J. Agardh (Araki and Nisizawa 1996). Therefore, the majority of the algae used in this study were investigated for the first time.

Materials and Methods

Samples of marine algae were collected in November 1995 from Bodega Bay in the vicinity of Bodega Marine Laboratory, University of California, Davis. Freshly collected algae were thoroughly cleaned to remove epiphytes and sand particles, and then heated for 2 minutes in boiling water to inactivate enzymes. Lipids were extracted by homogenizing the algae with chloroform-methanol (1:2 v/v) according to the procedure of Bligh and Dyer (1959).

Fatty acids were converted to fatty acid methyl esters (FAMEs) as described by Carreau and Dubacq (1978), purified by thin-layer chromatography using benzene as solvent and analyzed by gas-liquid chromatography. A gas chromatograph GC-9A (Shimadzu, Japan) equipped with a flame-ionization detector and with a data station Chromatopac C-R3A was used. Fused silica capillary columns (30 m x 0.25 mm) coated with Supelcowax 10 and SPB-5 were used at operating temperatures of 210° and 220 °C, respectively, with helium as the carrier gas and split ratio 1/30. Individual peaks of FAMEs were identified by the comparison of the retention times and equivalent chain length values (Christie 1988) with those of authentic standards. Argentation thin-layer chromatography was also used for double bond identification of fatty acids (Dudley and Anderson 1975).

Analyses were done in duplicate and data are expressed as means. Statistical analysis of data was performed for the fatty acids of fronds and stips of *Macrocystis integrifolia* Bory and values reported are means $\pm$ SD, where $n = 3$, $P < 0.05$.

Results and Discussion

The algal species examined and their total lipid contents are shown in Table I.

Red algae

We examined the fatty acids of 7 red algal species belonging to the orders Cryptonemiales, Gigartinales and Ceramiales. They had similar fatty acid patterns with four dominant FAs – palmitic (16:0), oleic (18:1n-9), arachidonic (20:4n-6) and eicosapentaenoic (20:5n-3) (Table II). These FAs together accounted for 76.9–89.1 % of the total FAs, whereas C_{18} PUFAs were present as minor components. Oleic acid was only a major FA in *Plocamium violaceum*. Eicosapentaenoic acid was the most abundant fatty acid in all algal species from California. Its content varied from 27.8 % in *Prionitis linearis* to 45.4 % of the total FAs in *Iridaea cordata*. The two *Prionitis* species and *Cryptopleura violaceae* had a high content of arachidonic acid (19.4–23.4 % of the total FAs), although it was not the dominant fatty acid.

Plocamium violaceum accumulated dihomo-γ-linolenic acid (20:3n-6) at 4.5 % of the total FAs, a level which far exceeds the content (less than 2.0 %) found in all the other red algal species examined (Jamieson and Reid 1972, Ackman 1981, Khotimchenko and Vaskovsky 1990, Fleurence *et al.* 1994). The literature data on the content of 20:3n-6 in *Plocamium* species are very contradictory. Previously, only 0.6 % of this acid was found in *P vulgare* Linnaeus from the Senegalese coast (Aknin *et al.* 1990), whereas it made up 5.3 % of the total FAs in *P telfairiae* Harvey from the Yellow Sea (Vaskovsky *et al.* 1996). The real reasons for this variation are unknown. Perhaps, environmental factors influence the 20:3n-6 content in *Plocamium* species, because water temperatures in the Yellow Sea and the Pacific coast of California are lower than those of the Senegalese coast. It is known that lower water temperature is favorable for the biosyntheses of PUFAs in algae (Harwood 1984).

Unexpectedly high levels of cis-vaccenic acid (18:1n-7) – 8.9 % of the total FAs were observed in *Odonthalia floccosa*, whereas this acid did not exceed 3.0 % of the total FAs in other species. Comparable amounts of 18:1n-7 acid (7.7 and 8.2 %) were reported in the past for only two *Polysiphonia* species (Ackman and McLachlan 1977, Johns *et al.* 1979). Further research is needed to examine the distribution of 18:1 isomers in red algae because the position of the double-bond in monounsaturated FAs may be helpful in chemo-taxonomic investigations.

A comparison of the FA compositions of *Iridaea cordata*, *Gigartina harveyana*, *Plocamium violaceum* and *Odonthalia floccosa* with those of species belonging to the same genera and collected from other regions of the World Ocean (Jamieson and Reid 1972, Aknin *et al.* 1990, Khotimchenko and Vaskovsky 1990, Vaskovsky *et al.* 1996) showed that algae from California had the highest levels of C_{20} PUFAs, mainly eicosapentaenoic acid. Only *Cryptopleura violaceae* from this area had a lower proportion of 20:5n-3 (32.5 %) and a higher content of 20:4n-6 (19.4 % of total FAs), than *C. ramosum* J. Agardh from Scotland (50.9 and 3.8 %, respectively) (Jamieson and Reid 1972). However, eicosapentaenoic acid predominated in both species.

Our results are in agreement with earlier conclusions that a dominance of C_{20} PUFAs, chiefly 20:4n-6 and 20:5n-3, is characteristic of red algae. Similar fatty acid profiles have been reported for members of Rhodophyta collected from Australian waters (Johns *et al.* 1979), the Mediterranean coast of Israel (Levy *et al.* 1992), the Black Sea (Stefanov *et al.* 1988), the Sea of Japan (Kaneniwa *et al.* 1987, Khotimchenko and Vaskovsky 1990) and other regions of the World Ocean (Jamieson and Reid 1972, Ackman 1981, Fleurence *et al.* 1994, Vaskovsky *et al.* 1996).

Table I. List of algae investigated.

	Total lipids (mg. g^{-1} dry wt)
Rhodophyta	
Cryptonemiales	
Prionitis lanceolata Harvey	29.0 ± 3.0
P linearis Kylin	39.4 ± 2.9
Gigartinales	
Iridaea cordata (Turner) Bory	15.1 ± 0.9
Gigartina harveyana (Kützing) Setchell *et* Gardner	6.4 ± 1.2
Plocamium violaceum Farlow	46.4 ± 3.9
Ceramiales	
Odonthalia floccosa (Esper) Falkenberg	16.8 ± 2.5
Cryptopleura violaceae (J. Agardh) Kylin	27.8 ± 2.1
Phaeophyta	
Ectocarpales	
Analipus japonicus (Harvey) Wynne	49.6 ± 4.2
Laminariales	
Laminaria dentigera Kjellman	34.3 ± 3.6
Hedophyllum sessile (C. Agardh) Setchell	68.1 ± 5.3
Macrocystis integrifolia Bory	28.5 ± 2.1
Postelsia palmaeformis Ruprecht	46.8 ± 3.6
Alaria marginata Postels *et* Ruprecht	25.5 ± 2.7
Egregia menziesii (Turner) Areschoug	31.7 ± 3.1
Fucales	
Fucus distichus Linnaeus	32.8 ± 3.3
Cystoseira osmundacea (Turner) C. Agardh	24.4 ± 2.0
Chlorophyta	
Ulvales	
Ulva lactuca Linnaeus	30.6 ± 3.0
Enteromorpha compressa (Linnaeus) Greville	52.2 ± 3.9
Siphonocladales	
Chaetomorpha linum (Muller) Kützing	60.0 ± 5.7

Data are expressed as means ± s.d., where n = 3.

Brown algae

The major FAs encountered in the brown algae collected from Bodega Bay on the coast of California were 16:0, 18:1n-9 and PUFAs with 18 (18:2n-6, 18:3n-3, 18:4n-3) and 20 (20:4n-6, 20:5n-3) carbon atoms. This is in accordance with the results obtained for other brown algae taken from different regions: Scotland (Jamieson and Reid 1972), Black Sea (Dembitsky *et al.* 1990), the French Brittany coast (Fleurence *et al.* 1994) and Russian Far East (Khotimchenko 1998). Ratios between these acids showed strong variations among different species, but polyenoic C_{18} and C_{20} fatty acids of the n-3 and n-6 series predominated in all species, except *Hedophyllum sessile*. Their content varied from 40.2 % to 64.8 % of the total FAs

Table II. Fatty acid composition of Rhodophyta (% of the total FAs): *Prionitis linearis* (1), *Prionitis lanceolata* (2), *Iridaea cordata* (3), *Gigartina harveyana* (4), *Plocamium violaceum* (5), *Odonthalia floccosa* (6), *Cryptopleura violaceae* (7).

Fatty acid	Algal species						
	1	2	3	4	5	6	7
14:0	3.0	2.1	2.4	3.0	6.5	2.3	3.7
16:0	26.7	27.7	29.9	28.6	29.7	28.6	29.4
16:1n-7	0.6	0.6	0.3	0.8	2.4	1.7	1.5
18:0	0.9	1.0	1.8	1.7	0.9	0.8	0.9
18:1n-9	6.2	6.3	8.5	12.5	1.8	5.3	4.4
18:1n-7	3.0	2.6	0.8	0.8	1.5	8.9	1.2
18:2n-6	0.7	1.0	0.8	1.6	0.6	1.4	0.6
18:3n-6	0.6	1.1	0.5	0.6	0.5	0.4	0.5
18:3n-3	0.2	0.2	0.2	0.2	0.5	0.2	0.2
18:4n-3	0.2	0.2	0.2	0.2	0.7	0.5	0.2
20:2n-6	1.3	0.5	0.4	0.4	0.4	0.1	0.1
20:3n-6	1.5	1.3	0.6	0.2	4.5	0.5	1.4
20:4n-6	23.4	19.8	5.3	10.4	8.2	14.8	19.4
20:5n-3	27.8	32.2	45.4	37.2	37.2	31.6	32.5
Other*	3.7	3.4	2.9	1.8	4.6	2.9	4.0

* 15:0, br-15:0, br-16:0, 17:0, 20:0, 14:1, trans-16:1, 16:2, 20:1, 20:3n-3, 20:4n-3.

Table III. Fatty acid composition of Phaeophyta (% of the total FAs): *Analipus japonicus* (1), *Laminaria dentigera* (2), *Hedophyllum sessile* (3), *Macrocystis integrifolia* (whole thallus) (4), *Postelsia palmaeformis* (5), *Alaria marginata* (6), *Egregia menziesii* (7), *Fucus distichus* (8), *Cystoseira osmundacea* (9).

Fatty acid	Algal species								
	1	2	3	4	5	6	7	8	9
14:0	3.9	2.6	5.8	8.0	4.1	3.5	3.8	8.4	3.8
15:0-branch	0.9	0.8	0.2	1.5	0.3	1.1	1.5	0.6	1.1
16:0	19.9	29.6	20.1	16.4	26.1	14.9	20.8	19.6	22.5
16:1n-7	0.7	2.0	1.0	1.4	0.8	0.7	1.0	1.8	2.1
16:1-trans	0.9	0.3	0.2	1.2	0.4	1.1	0.5	0.4	0.5
18:0	0.7	2.4	2.5	1.1	2.2	1.1	1.6	0.8	0.8
18:1n-9	10.9	20.0	40.7	12.2	23.6	11.1	13.6	16.7	11.8
18:2n-6	8.4	5.1	6.5	4.3	9.9	3.7	6.0	7.7	5.8
18:3n-6	0.5	0.6	1.2	1.0	0.6	0.7	0.6	0.4	0.9
18:3n-3	7.6	4.1	2.1	6.5	5.9	8.7	8.7	7.5	9.7
18:4n-3	13.4	8.9	3.6	15.5	7.7	20.3	13.1	6.7	12.5
20:2n-6	0.4	0.9	0.4	1.3	0.1	0.6	0.7	0.6	0.3
20:3n-6	0.7	0.4	0.5	0.5	0.7	0.3	0.4	0.6	0.3
20:4n-6	13.8	9.5	9.6	14.3	7.9	14.2	14.7	14.1	18.6
20:4n-3	1.1	0.3	0.1	0.4	0.3	0.7	0.8	0.6	0.5
20:5n-3	13.2	10.4	3.1	8.7	7.2	15.5	9.9	10.9	5.5
Other*	3.6	2.1	2.4	5.7	2.2	1.8	2.3	2.6	3.3
$\sum$ PUFA(n-3)	35.3	23.7	8.9	31.1	21.1	45.2	32.5	25.7	28.2
$\sum$ PUFA(n-6)	23.8	16.5	18.2	21.4	19.2	19.5	22.4	23.4	25.9

* 15:0, i-16:0, ai-16:0, 17:0, 20:0, 14:1, 16:2, 18:1n-7, 20:1, 20:3n-3.

(Table III). The PUFAs of the n-3 series were more abundant than n-6 PUFAs, the highest content of n-3 PUFAs being found in *Alaria marginata* at 45.2 %. Three brown algal species contained approximately equal proportions of n-3 and n-6 PUFAs: *Postelsia palmaeformis*, *Fucus distichus* and *Cystoseira osmundacea*.

Hedophyllum sessile differed from other brown algae by having the lowest level of PUFAs, especially of the n-3 series (8.9 % of the total FAs). On the other hand, oleic acid was the major fatty acid component and accounted for 40.7 % of the total FAs. Oleic acid is commonly one of the major fatty acids in brown algae (Jamieson and Reid 1972, Kaneniwa *et al.* 1987, Dembitsky *et al.* 1990, Fleurence *et al.* 1994, Khotimchenko 1998), but its content only sometimes exceeded 20.0 % of the total FAs, as for example, in *Postelsia palmaeformis* (23.6 %, see Table III) or in *Costaria costata* (Turner) Saunders (21.4 %) (Khotimchenko 1998). The high concentration of oleic acid, which made up 38.0 % of the total FAs had been previously reported in algae from the genus *Pelvetia* and the authors suggested that this feature in FA composition is typical of *Pelvetia* species (Jamieson and Reid 1972, Khotimchenko 1998). Also, it was shown that the content of oleic acid in *Fucus* varied by season, reaching a maximum of 34.1 % in *F. serratus* in September (Kim *et al.* 1996) and 38.2 % of the total FAs in *F spiralis* in April (Jamieson and Reid 1972). Hence, further study is needed to elucidate whether the high content of oleic acid is a taxonomic characteristic of the fatty acid composition of *Hedophyllum sessile* or is the result of the influence of seasonal or environmental factors.

The fatty acids of most of the brown algal species from this area were investigated for the first time. We have previously only studied the fatty acids of *Analipus japonicus* from the Sea of Japan collected in summer (Khotimchenko 1998). It differed in n-3 and n-6 PUFAs from the same species taken in Bodega Bay in autumn. *Analipus japonicus* from California was richer in PUFAs of the n-3 series (35.3 % of total FAs) than the same alga from the Sea of Japan (21.1 %). This may be the effect of water temperature because it is known that algae accumulate PUFAs when there is a decrease in environmental temperature (Harwood 1984, Kayama *et al.* 1985).

The FA patterns of *Laminaria dentigera, Fucus distichus* and *Cystoseira osmundaceae* from the coast of California were similar to *Laminaria sp., Fucus sp.* and *Cystoseira sp.* taken from different regions (Jamieson and Reid 1972, Dembitsky *et al.* 1990, Fleurence *et al.* 1994, Khotimchenko 1998, Moreno *et al.* 1998). However, they differed in the ratios of the main FAs. The fatty acid composition of *Alaria marginata* from the California coast did not differ significantly from that of *A. angustata* Kjellman from the Russian Far East coast, e. g. PUFAs of n-3 series made up 45.2 % of the total FAs in *A. marginata* and 49.6 % in *A. angustata* (Khotimchenko 1998).

Marine brown algae from the coast of California are very large seaweeds. Therefore, we compared the FA composition in fronds and stipes of *Macrocystis integrifolia* – one of the most widely used Phaeophyta (Chapman and Chapman 1980). We found that fronds and stipes of this alga differed in their FA ratios. The stipes contained a greater proportion of saturated FAs (26.9 $\pm$ 2.0 %) and total n-6 PUFAs (26.9 $\pm$ 1.8 % of total FAs) than the fronds (20.1 $\pm$ 1.1 % and 19.1 $\pm$ 1.2 %, respectively). The greatest variations in the FA ratio between stipes and fronds of *M. integrifolia* were found for PUFAs of the n-3 series (18:3, 18:4 and 20:5) and oleic acid. The proportion of n-3 PUFAs was higher in fronds, where they accounted for 48.8 $\pm$ 3.1 % of the total FAs, whereas the concentration of these FAs was lower in stipes (20.8 $\pm$ 1.6 %). On the contrary, the stipes of this alga were richer in oleic acid (18.4 $\pm$ 1.1 %) as compared with fronds (6.7 $\pm$ 0.9 %). A similar difference in the FA ratios between different parts of the algal thallus has been reported for *Laminaria japonica* Areschoug from the Sea of Japan (Khotimchenko and Kulikova 2000) and *Ecklonia muratii* Feldmann from the Senegalese coast (Miralles *et al.* 1989). Thus, these results show that the highest amounts of n-3 PUFAs in these brown algal species are concentrated in the fronds.

Green algae

Green algae have a high concentration of C_{16} and C_{18} polyunsaturated FAs (Jamieson and Reid 1972, Ack-

Table IV. Fatty acid composition of Chlorophyta (% of the total FAs).

Fatty acid	*Ulva lactuca*	*Enteromorpha compressa*	*Chaetomorpha linum*
14:0	0.4	0.6	9.7
15:0-branch	2.2	2.3	0.4
16:0	23.5	23.1	23.0
16:1n-7	1.1	1.1	0.7
16:1-trans	1.9	1.5	0.6
16:3n-3	0.3	2.8	0.0
16:4n-3	16.2	13.6	13.8
18:1n-9	1.3	1.4	8.7
18:1n-7	8.0	6.3	1.1
18:2n-6	2.3	3.8	28.6
18:3n-6	0.4	0.7	1.0
18:3n-3	11.1	21.9	0.5
18:4n-3	22.1	12.1	0.6
20:2n-6	0.3	0.2	1.3
20:4n-6	0.3	0.5	1.2
20:5n-3	1.0	1.4	1.3
22:5n-3	2.9	2.7	1.9
Other*	4.7	4.0	5.6
$\sum$ PUFA (n-3)	53.6	53.9	18.2
$\sum$ PUFA (n-6)	3.3	5.1	32.1

* 15:0, br-16:0, 17:0, 18:0, 20:0, 14:1, 17:1, 20:1, 16:2, 20:3n-6, 20:3n-3, 20:4n-3.

man and MaLachlan 1977, Aknin *et al.* 1992, Khotimchenko 1993). This peculiarity of the FA composition was observed for the three species of Chlorophyta from the coast of California examined in our study. The members of the order Ulvales (*Ulva lactuca* and *Enteromorpha compressa*) had similar fatty acid patterns, but differed in their FA ratios. They contained hexadecatrienoic (16:3n-3) and even more hexadecatetraenoic (16:4n-3) acids, and had 18:1n-7/18:1n-9 ratios higher than 1 (Table IV). These algal species were also rich in C_{18} PUFAs – α-linolenic (18:3n-3) and octadectetraenoic (18:4n-3). Octadecatetraenoic acid was the main polyunsaturated acid in *Ulva lactuca,* whereas α-linolenic acid predominated in *Enteromorpha compressa*. A similar fatty acid profile was reported for *Ulva lactuca* from Scotland (Jamieson and Reid 1972), Australia (Johns *et al.* 1979), and Senegal (Aknin *et al.* 1992), and for *Enteromorpha compressa* from Scotland (Jamieson and Reid 1972) and China (Vaskovsky *et al.* 1996). However *Ulva lactuca* and *Enteromorpha compressa* from the coast of California were richest in polyunsaturated FAs of (n-3) series which made up 53.6 % and 53.9 % of the total FAs, respectively.

The fatty acid composition of *Chaetomorpha linum* (order Siphonocladales) differed from that of *Ulva lactuca* and *Enteromorpha compressa*. This alga had a high proportion of 14:0, and only one polyenoic fatty acid with 16 carbon atoms – 16:4n-3. The level of 18:1n-9 exceeded that of 18:1n-7. It was poor in both α-linolenic and octadecatetraenoic acids (0.5 and 0.6 % of total FAs, respectively), and linoleic acid (18:2n-6) was the most abundant PUFA (28.6 % of total FAs). Similar results were reported for two species of the genus *Chaetomorpha* collected from the Sea of Japan (Khotimchenko 1993), in which linoleic acid was also the major PUFA and its content ranged from 20.5 to 29.2 % of the total FAs, whereas the concentration of 18:3 and 18:4 together did not exceed 2.0 %. Previously we assumed that such a ratio between C_{18} PUFAs was typical of algae of the genus *Chaetomorpha*. The fatty acid composition of *C. linum* studied here is added evidence in support of our assumption.

Green algae from the coast of California, as well as other members of the Chlorophyta contained long-chain PUFAs – arachidonic, eicosapentaenoic and docosapentaenoic (22:5n-3) acids as minor components; the sum of which did not exceed 4.5 % of all the FAs.

Thus green algae from California had similar features of FA composition as was reported earlier for other green algae collected elsewhere (Jamieson and Reid 1972, Johns *et al.* 1979, Aknin *et al.* 1992, Vaskovsky *et al.* 1996).

In conclusion, the taxonomic differences in the fatty acid composition of marine red, brown and green algae are supported by our study. A comparison of the FA compositions of algae from different regions of the world and from the coast of northern California showed that, in general, and independently of the geographical source, algae had similar FA profiles typical of each phylum of seaweeds. Habitat conditions may affect the quantitative characteristics of the FA profiles, but the differences appear to be different for the various algal species. In spite of the variability of the FA composition of algae under different habitat conditions, their specific features remain constant. The results have practical value. Marine algae are rich in PUFAs of the n-3 and n-6 series, which are considered essential fatty acids for humans and animals. Some of these FAs (20:3n-6, 20:4n-6, 20:5n-3) have high biological activity and are converted into eicosanoids. In addition, PUFAs are of interest in cosmetics as components of sun lotions and as regenerating and anti-wrinkle products (Helme 1990). Because of the huge and renewable biomass, seaweeds are a potential source of FAs for biotechnology and a dietary source of essential fatty acids.

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