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DIETARY FIBRE FROM EDIBLE SEAWEEDS: CHEMICAL STRUCTURE, PHYSICOCHEMICAL PROPERTIES AND EFFECTS ON CHOLESTEROL METABOLISM

A. Jiménez-Escrig B. Sc. [1] and F. J. Sánchez-Muniz Ph. D. Prf. [2]
[1]Departamento de Metabolismo y Nutrición. Instituto del Frío. Consejo Superior de Investigaciones Científicas. C/ Ramiro de Maeztu s/n. 28040-Madrid. España.
[2]Departamento de Nutrición y Bromatología I (Nutrición). Sección Lípidos. Facultad de Farmacia. Universidad Complutense. 28040-Madrid. España.

ABSTRACT

This brief review outlines the chemical structure, physicochemical properties and effects of seaweed polysaccharides on serum cholesterol levels. Some seaweed polysaccharides are used by the food industry as texture modifiers because of their high viscosity and gelling properties. In Asia, seaweeds have been used for centuries in salads, soups and as low-calorie dietetic foods. The dietary fibre which constitutes 25-75% of the dry weight of marine algae and represents their major component, is primarily soluble fibre. Nowadays, dietary fibre from different sources is known to decrease the risk of coronary heart disease, mainly due to its characteristics of dispersibility in water (water-holding capacity), viscosity, binding ability, absorptive capacity, faecal bulking capacity and fermentability in the alimentary canal. Indigestible viscous seaweed polysaccharides such as alginates, carrageenans and funorans, which are capable of forming ionic colloids, have shown positive effects on serum lipid levels in rats. The capacity of seaweed polysaccharides to lower serum cholesterol levels seems to be due to their ability to disperse in water, retain cholesterol and related physiologically active compounds and inhibit lipid absorption in the gastrointestinal tract.

Key Words: Edible seaweeds; Dietary fibre; Cholesterol.

INTRODUCTION

Utilisation of algae has increased considerably over the past fifty years, with the consequent increase in applied research in various related fields. The most important investigations have dealt with phycocolloid production and algal cultivation, with the aim at producing raw material and foodstuffs (1). The total volume of seaweeds used in foods is considerably greater than that used in industrial applications, in terms of weight and especially monetary value.

Corresponding Autor Professor Francisco J. Sánchez-Muniz. Departamento de Nutrición y Bromatología I (Nutrición). Sección Lípidos. Facultad de Farmacia. Universidad Complutense. 28040-Madrid. España. (Ph: 34-91-3941828/34-91-3941910; Fax: 34-91-3941732; E-mail: frasan@eucmax.sim.ucm.es)

More than 2 million tonnes per year of fresh seaweed are processed to obtain food products, mainly in the Far East, while about 1.5 million tonnes per year are used for industrial production, in order to obtain phycocolloid alginate agar and carrageenan. The value of the food products is more than six times that of the industrial commodities (2). In Asia, seaweeds have been used in human nutrition since ancient times. Because of the documented association between high blood lipid and lipoprotein levels and the risk of coronary heart disease (CHD), research has focused mainly on the influence of dietary fibre on lipid metabolism. Despite the high content in dietary fibre of seaweeds (from 25% to 75% of dry matter), data concerning the effects of algal polysaccharides on serum cholesterol levels are scarce. In addition, the wide spectrum of seaweed polysaccharides may exhibit diverse metabolic effects.

THE CONCEPT OF DIETARY FIBRE

While literature on dietary fibre abounds no one precise definition of dietary fibre exists (3). The term "dietary fibre" was first used in 1953, in place of "crude fibre", to refer to the non-digestible residue in foods (4). Since 1974, when Burkitt, Walker and Painter first suggested a relationship between the prevalence of a range of diseases, including cardiovascular disease, colon cancer and diabetes, in developed communities and low dietary fibre consumption, numerous studies have demonstrated its chemical and nutritional importance (5).

In 1974, dietary fibre was defined as that portion of foodstuffs, derived from plant cells and resistant to hydrolytic digestion by the alimentary enzyme system in human beings, which consists of hemicelluloses, celluloses, lignins, oligosaccharides, pectins, gums and waxes (6). Cummings and Englyst (3) suggest that for analytical purposes, dietary fibre should be defined as the non-starch polysaccharides (NSP) in plant foods, since the best index of plant cell-wall material in food is its NSP content, which can be accurately determined. However, the NSP fraction excludes resistant starches which are formed during processing, as well as lignin. These are not normally digested by humans and therefore must also be considered dietary fibre (4). Nowadays, some researchers define dietary fibre as an indigestible fraction which contains oligosaccharides and resistant starches, resistant proteins, and associated compounds such as polyphenols (7, 8).

STRUCTURAL ASPECTS OF DIETARY FIBRE

Dietary fibre is a complex mixture of chemical entities, and its concentration and composition in different sources are neither constant nor uniform (4). This physical and chemical diversity explains the number and complexity of the physiological roles attributed to dietary fibre. With regard to polysaccharides, each type of dietary fibre is characterised by its sugar residues and the nature of the bonds between them (Table 1).

Marine algae polysaccharides

Marine macroalgae or seaweeds are classified into three groups: brown algae (Phaophyceae), red algae (Rhodophyceae), and green algae (Clorophyceae) (11). Algae belonging to each group differ with regard to their reserve and cell-wall polysaccharides. The seaweeds most used in foods include brown algae such as Laminaria (Konbu), Undaria (Wakame) and Hijiki (Hiziki) and species of the red algae Porphyra (Nori). Their Japanese names, used world-wide, are shown in parentheses (12).

TABLE 1

Summary of the structural composition of different types of fibre (4, 7, 9, 10)

Fibre	Main unit	Branch units
Cellulose	β-(1,4)glucose	
β-glucans	β-(1,3)glucose and β-(1,4)glucose	
Hemicelluloses		
Arabinoxilans	Galactose	Arabinose
Xiloglucans	Glucose	Xilose
Galactomannans	Mannose	Galactose, glucose
Pectins	D-galactouronic with methoxi groups	Arabinose Galactose
Gums		
Guar	Galactomannan	
Alginates	β-(1,4)-D-mannuronic acid and α-(1,4)-L-guluronic acid	
Carrageenans	α-(1,3)-galactose acid and β-(1,4,3,6)-anhydro-D-galactose	
Agar	D-galactose and (3,6)-anhydro-L-galactose	
Funorans	galactose sulphate	
Laminarans	(1,3)-β-D-glucose and (1,6)-β-D-glucose	Mannitol
Fucoidans		
Xylofucoglicouronans	(1,2)-α-1-fucose-1-sulphate	D-xylose, D-galactose, D-manosse
Glicouronofucogalactans	β-(1,4)-D-mannuronic acid and 3-D-xylosyl-L-fucose-4-sulphate (1,4)-D-galactose and L-fucosyl-3-sulphate	
Lignin	Polyphenols and Malliard Products	

Dietary fibre from brown algae is essentially composed of four families of polysaccharides: laminarans, alginates, fucans and cellulose. Laminarans, reserve polysaccharides found in brown algae, are composed of (1,3)–β-D-glucose with some (1,6)-linkages and in which some of the reducing ends are replaced by mannitol. The major matrix component of brown seaweeds is a gelling polyuronide, alginate, consisting of alternating sequences of β-(1,4)-D-mannuronic acid, its C5 epimer α-(1,4)-L-guluronic acid and 20-30 units of the uronic acids mentioned. On the other hand, alginate may consist of only 20-30 units of these uronic acids. The proportion of these components varies depending on the source of the alginate.

The chemical structure of fucans is very heterogeneous, and these polysaccharides can be classified into three major groups: fucoidans, xylofucoglycuronans and glycorunogalactofucans.

Fucoidans are primarily composed of (1,2)-α-L-fucose-4-sulphate with branching or a sulphate ester group on C3, and contain very small quantities of D-xylose, D-galactose, D-mannose and uronic acids. Xylofucoglycuronans or ascophyllans consist of a polyuronide backbone, mainly poly-β-(1,4)-D-mannuronic acid branched with 3-O-D-xylosyl-L-fucose-4-sulphate or occasionally uronic acid. Glycuronogalactofucans are composed of linear chains of (1,4)-D-galactose branched at C5 with L-fucosyl–3-sulphate or occasionally uronic acid. Cellulose constitutes brown algae cell walls (9). Cell walls of red algae are composed of sulphated galactans (carrageenans and agar), xylans, mannans and cellulose, while their reserve polysaccharide consists of starch (13).

Carrageenan is a generic term for a complex family of polysaccharides, extracted from a number of different red seaweeds, consisting of sulphated linear galactans in which α-(1,3)-galactose alternates with β-(1,4,3,6)-anhydro-D-galactose. The carrageenans used most commercially (κ-, λ- and ι- carrageenans), differ in the amount and position of their ester sulphate substitutes and (3,6)–anhydrogalactose content. Agars are mixtures of polysaccharides extracted from certain red seaweeds, particularly species of Gracilaria and Gelidium, composed of D-galactose and 3,6-anhydro-L-galactose (11).

Green algae contain starch, cellulose, xylans, mannans and ionic polysaccharides which contain sulphate groups and uronic acids. Rhamnose, xylose, galactose and arabinose are also found in this type of algae (13).

SOLUBLE AND INSOLUBLE DIETARY FIBRE

Dietary fibre can be classified as either soluble or insoluble, based on whether it forms a dispersion when mixed with water (soluble fibre), or not (insoluble fibre). While soluble and insoluble fractions share many of the same physical properties, soluble fibre can be distinguished by its ability to form viscous gels in the intestinal tract. Insoluble fibre does not exhibit viscosity but can instead be characterised by its faecal-bulking capacity. Both forms of fibre share the ability to bind water or mineral cations and may be used by colonic microflora as fermentable substrate (7).

Soluble dietary fibre can include, in addition to xyloglucans and galactomannan hemicelluloses, β-glucans and pectic substances, gums and mucilages, while celluloses, lignin arabinoxylan hemicelluloses and resistant starch comprise the insoluble fraction (10). Marine algae, rich in polysaccharides which are indigestible by humans, appear to be good sources of soluble dietary fibre (13). Total dietary fibre content of the main edible seaweeds ranges between 25%-75% (on a dry weight basis), of which water-soluble fibre constitutes 51%-85% (14, 15). Dietary fibre values of some seaweeds and some terrestrial earth vegetables are shown in Table 2.

GENERAL PHYSICAL PROPERTIES AND GASTROINTESTINAL FUNCTION OF ALGAL POLYSACCHARIDES

The physical properties of dietary fibre depend on the chemical nature of its components. The physical and chemical characteristics of dietary fibre will, in turn, dictate the specific local response in the gut and the associated systemic reactions which may be expected with ingestion of a particular type of fibre (See Table 3). These physicochemical qualities include dispersibility in

water (water-holding capacity), viscosity, binding and absorptive capacity, faecal bulking capacity and fermentability (7,18). Dietary fibre of marine algae differs chemically and physicochemically from that of terrestrial plants and may thus have different physiological effects in man (13).

TABLE 2

Content in dietary fibre of some seaweeds, fruits, vegetables, legumes and cereals expressed in % of dry weight

	Insoluble Fibre	Soluble Fibre	Total Fibre	References
Nori	16.8	17.9	34.7	
Hijiki	16.3	32.9	49.2	
Wakame	5.3	30.0	35.3	
Ulva lactuta	16.8	21.3	38.1	(13)
Enteromorpha spp.	16.2	17.2	33.4	
Himantalia elongata	7.0	25.7	32.7	
Eisenia byciclis	14.9	59.7	74.6	
Whole soy	65.24	7.08	72.32	
Whole wheat	41.59	2.87	44.46	
Whole corn	87.47	0.40	87.87	
Rice	0.75	0.19	0.94	
Beans	25.64	10.85	36.49	
Brussels sprouts	30.23	6.16	36.39	(16, 17)
Chickpeas	16.69	1.35	18.04	
Onions	13..32	3.59	16.89	
Potatoes	4.85	2.14	6.99	
Apricots	44.92	26.43	71.35	
Peaches	39.53	27.30	66.83	
Apples	55.57	18.56	74.13	

Dispersibility in water and viscosity

The major matrix component in brown algae is a gelling polyuronide called alginate. Alginate forms strong gels in the presence of excess calcium cations (9). Guluronic acid-rich sodium alginate is more soluble in water than mannuronic acid-rich sodium alginate. Solubility seems to be a leading cause of retardation of food intake in alginate diets, due to the gelling of alginic acid in the stomach. Animals fed guluronic acid-rich alginate display a significantly lower food intake and grow more slowly than those consuming mannuronic acid-rich alginate (19, 20) . In addition, sodium alginate slows gastric evacuation in humans (21). Regarding red seaweeds κ-carrageenan forms strong gels in the presence of potassium, whereas λ-carrageenan, a non-gelling agent, forms viscous solutions. ι-carrageenan produces elastic gels in the presence of calcium (11).

The water-holding capacity of seaweeds varies according to the species in question. Dried marine algae can swell to about 20 times their volume in dry matter when exposed to water (22). The edible alga wakame, with a high soluble fibre content, presents values of 38.6 g/g dry weight. However, gastric pH levels lower the water-holding capacity of seaweeds (23).

Binding capacity

The binding capacity that diverse fibre sources display toward bile salts is well known. The overall binding process involves attachment of bile salts to superficial fibre molecules, their subsequent diffusion into the cell wall matrix and their retention within the matrix (4).

Suzuki et al. (23) studied the binding of bile acids to twelve species of green, brown and red algae. These in vitro experiments demonstrated that the highest degree of binding, which occurred between cholate and the red alga Nori (12.6-15.5%), was more than double that observed in the case of other seaweeds, with the exception of the green alga Ao Nori (9.7%). The brown algae Hiziki and Konbu, which showed the lowest binding capacity, did not adsorb sodium cholate. Binding of bile acids to certain types of fibre is known to be influenced by pH levels. The strongest binding occurs at low pH levels, and weakens as bile acid polarity increases (23).

The reduced bioavailiability of mineral cations when dietary fibre is consumed has long been associated with the binding of minerals to fibre. Dietary fibre molecules with free carboxyl, hydroxyl or amino groups display the greatest affinity for mineral cations. Among the different sources of dietary fibre, pectins appear to have the greatest mineral-binding potential. Highly methoxylated forms of pectin are not as likely to bind minerals as poorly esterified forms which have a greater number of free uronic acid residues (7). In vitro studies have demonstrated that some brown seaweed fibre is capable of releasing potassium and scavenging sodium from the environment. Brown seaweed fibre can adsorb 59 mg of sodium per gram, and may, therefore, have some exchange capacity (24). Alginate displays particular affinity for calcium, strontium and barium ions which induce a conformational transformation of the polyuronide chains into "egg-boxes" in which the cations are strongly chelated. Aggregation of alginate chains leads to the formation of gels (9).

Fermentability

Bacterial fermentation in the large bowel produces short chain fatty acids (Table 3). Primary fermentation products include acetic, propionic and butyric acids, and carbon dioxide, hydrogen and methane gases. These products change the physicochemical environment of the large bowel. The acids produced lower the pH and the availability of carbohydrate substrates produces a shift in bacterial metabolism, promoting the growth of some organisms at the expense of others (25).

Insufficient research has been done on the fermentation of algal fibres by human or rat faecal flora. A recent study (26) has shown that high concentrations of fucose and sulphate as well as their particular arrangement in brown algal fibre are probably responsible for their resistance to bacterial degradation. Alginates exhibit a particular fermentation pattern, taking 6h of latency phase in the production of gas and short chain fatty acids (SCFA) and showing that only 65% of degraded alginates were metabolised to SCFA (26). These results contradict the general assumption that water-soluble fibre is highly fermentable (27). Since algal fibre probably retains its physicochemical properties in the colon, its resistance to fermentation can lead to particular physiological effects (26). Another study of water-soluble polysaccharides from brown algae showed that human intestinal bacteria ferment sodium alginate and laminaran but not fucoidan and cellulose (28). Despite its high soluble fibre content, the green alga Ulva lactuca has displayed only modest fermentability in rats (29).

TABLE 3

Characteristics of dietary fibre and its relationship to local and systemic effects (7, 18)

Characteristics	Local effects in the bowel	Systemic effects
Dispersibility in water and viscosity.	Slows entry of gastric contents. Alters mixing of contents.	Slows digestion and absorption of carbohydratesand lipids. Associated with cholesterol reductionin plasma and blunting of glycaemic response.
Bulk.	Alters mixing and diffusion.	
Adsorb/bind Compounds.	Increases excretion of bile acids or other bound compounds.	
Fermentability.	Increases microbial mass and products of metabolism (e.g. CO_2, H_2, CH_4 and short chain acids). Induces microflora selection.	Associated with lowering cholesterol levels.

EFFECTS OF ALGAL POLYSACCHARIDES ON CHOLESTEROL METABOLISM AND HYPERTENSION

Effects on cholesterol metabolism

Ito and Tsuchiya (30) studied the effects of agar, sodium alginate, funoran, and carrageenan on plasma and faecal cholesterol levels in rats fed a basal diet of casein and sucrose in addition to a 1% cholesterol supplement for 28 days. The results are summarised in Table 4. Sodium alginate, funoran and carrageenan exhibited significant hypocholesterolaemic activity when included in the basal diet at levels of 1-10%, while agar was almost inactive. Sodium alginate reduced the absorption of cholesterol in the gut. This study also examined the hypocholesterolaemic effect of alginic acids at various degrees of polymerisation (Table 4). Results suggest that the greater the degree of polymerisation of the alginic acids, the more active they were in reducing plasma cholesterol and thus elevating the level of faecal cholesterol.

Moreover, the effect of alginic acid of lowering blood cholesterol levels in rats is due to the reduction of cholesterol absorption in the gut. Especially, it most be pointed out that sodium alginate at the lowest degree of polymerisation, supposedly absorbable by the gastrointestinal tract, proved to be rather hypercholesterolaemic in rats. The positive correlation between the degree of polymerisation of alginic acid and hypocholesterolaemic activity, and the fact that the decrease of faecal cholesterol coincides with a reduction of hypocholesterolaemic activity, strongly suggest that alginic acid impairs cholesterol absorption in the gut.

The effectiveness of alginic acid, funoran and carrageenan in increasing faecal cholesterol excretion is attributed to the fact that they are acidic polysaccharides which produce an indigestible ionic colloid. On the other hand, the neutral polysaccharide agar rarely forms ionic colloids and therefore does not increase faecal cholesterol levels. These algal polysaccharides are able to lower cholesterol due to their water dispersibility, their capacity to retain cholesterol and related physiologically active compounds and their ability to inhibit absorption in the gut.

In a related study, Kiriyama et al. (31) investigated the hypocholesterolaemic effect of free alginic acid, agar, Konbu (Laminaria japonica), Hiziki (Hijiki fusiformis) and Ao Nori (Entheromorpha prolifera) in rats fed hypercholesterolaemic diets for 5-8 days. Surprisingly, plasma

cholesterol levels in all groups receiving these diets were higher than those observed in rats fed a high-cholesterol diet without fibre (control group), although individuals fed Hiziki, Ao Nori and agar absorbed less cholesterol than the control group. Hepatic cholesterol levels were higher in test individuals than in control animals. These discrepancies with the study of Ito and Tsuchiya (30) mentioned above, may be due to different test conditions, such as differences in the duration of the feeding period, age and/ or breed of the test animals.

Suzuki et al. (19) studied the comparative effects of sodium alginates rich in guluronic and mannuronic acids on cholesterol levels in rats fed diets containing both alginates and cholesterol. Their results are summarised in Table 5. Guluronic acid-rich alginate significantly lowered the serum cholesterol concentration in relation to that of individuals fed the control diet (cholesterol but not fibre). On the other hand, mannuronic acid-rich alginate reduced this value only slightly. Rats fed both alginate diets consumed a significantly smaller amount of cholesterol than rats given diets without alginates. Therefore, the main reason for the reduction of serum cholesterol levels seems to have been the lower amount of cholesterol ingested. The dietary groups studied did not display significantly different HDL-cholesterol levels. The authors calculated an arteriosclerotic index (AI) from the ratio between VLDL-cholesterol plus LDL-cholesterol and HDL-cholesterol in serum. Guluronic acid-rich alginate gave rise to a significantly lower AI than mannuronic acid-rich alginate, but there were no significant differences between the indices of the diets with and without alginates.

TABLE 4

Effect of different algal polysaccharides on cholesterol metabolism in rats (30)

Diet	Fibre	Total plasma Cholesterol (mg/dL)	Faecal Cholesterol (g/100 g dry matter)
1%cholesterol	Without fibre	254.4±10.3	8.32±0.12
	1% Na-alginate	232.8±4.2	8.32±0.18
	3% Na-alginate	202.3±4.8	8.0±0.26
	10% Na-alginate	199.6±5.9	9.06±0.07
	3% agar	249.8±5.9	8.28±0.21
	10% agar	244.1±3.6	8.03±0.10
1%cholesterol	Without fibre	192.1±6.4	ND[1]
	1% funoran	178.1±6.4	
	3% funoran	151.9±3.5	
	1% carrageenan	163.9±4.5	
	3% carrageenan	134.7±8.1	
1% cholesterol	Without fibre	203.3±6.3	11.46±0.28
	3% Na-alginate (DP 417)[2]	158.1±3.5	12.08±0.28
	3% Na-alginate (DP 226)[2]	154.7±13.3	12.01±0.46
	3% Na-alginate (DP 13)[2]	210.1±14.0	10.30±0.54

[1] Not determined. [2] Polymerisation degree.

Ren et al. (32), evaluated the effect of seaweeds and algal polysaccharides on blood pressure and serum lipid levels in rats fed a saline solution along with a cholesterol-rich diet. Almost all the seaweeds studied displayed a marked antihypercholesterolaemic effect. In addition, serum high density lipoprotein (HDL) levels reached 46% in relation to the control value. However, seaweed components other than polysaccharides could be responsible for these results (35).

No significant difference in food intake was observed between the group given algal polysaccharides and the control group during the 28 day-long study period. At the end of the experiment, the body weight of animals fed the algal polysaccharide diets was slightly higher than that of the control individuals (32)

The effects of different algal polysaccharide diets on serum lipid levels in hypercholesterolaemic rats are shown in Table 5. AI of groups whose diets contained sulphated glucuronoxylorhaman, alginate, funoran, and porphyran decreased 53.0%, 49.0%, 43.0% and 27.0% in relation to the control value, respectively.

Total cholesterol (TC) levels were also lowered by the polysaccharide diets. TC dropped 36.0%, 35.0%, 32.0%, 23.0%, 12.0% and 5.0% below control group values in individuals fed funoran, sulphated glucuronoxylorhaman, alginate, porphyran, fucoidan, and agar, respectively (Table 5). TC values in the agar diet group were in approximately the same range as those of the control group. Polysaccharide diets lowered serum tryglicerides (TGL) as well as LDL-cholesterol levels. Individuals fed diets including funoran and glucuronoxylorhaman presented the lowest TGL levels (in the range of 54% and 36% of the control value, respectively), while those given the fucoidan and agar diets exhibited the smallest drop in TGL values: 20% and 2% below those of the control group, respectively (Table 5).

In contrast to the above results, HDL levels in individuals fed these polysaccharide diets were rather high. The greatest increase was observed with fucoidan. However, HDL values increased only minimally with the funoran and porphyran diets. The other polysaccharides induced a moderate rise above control levels (Table 5). It appears that polysaccharides (particularly polyionic ones) may retain dietary cholesterol thus facilitating its faecal excretion, which may, in turn, be related to the depression of blood cholesterol levels. Some seaweed polysaccharides prevented the reduction of serum HDL-cholesterol after a 4 week-long high cholesterol diet.

The same authors reported similar results in another study with funoran in rats (33) (Table 5). Funoran depressed TGL, LDL-cholesterol and AI levels in cholesterol-fed rats, while markedly increasing faecal cholesterol excretion. This suggests that the hypolipidaemic effect of funoran is due to prevention of dietary cholesterol absorption and enhancement of faecal cholesterol excretion.

Studying the effects of three forms of alginate (free acid, sodium and calcium salts) on serum lipids, Nishide (34) found that serum TC values in the sodium-alginate group were similar to those of the control group, whose diet contained 0.5% in cholesterol and 0.25% in bile salts (See Table 5). However, in the presence of calcium-alginate and alginic acid, TC levels were significantly higher than those of the control group. HDL-cholesterol levels increased significantly in all alginate groups. TGL values were higher in the alginic acid group than in control group, whereas slightly lower values were observed in the sodium and calcium alginate groups. Control animals excreted 26% of the initial cholesterol intake, while alginate group individuals eliminated between 34% and 37%. Rats fed the alginic acid diet exhibited the highest percentage of faecal cholesterol excretion. This suggests that alginic acid may display a greater capacity to bind cholesterol than its salts.

TABLE 5

Effect of different diets containing algal polysaccharides as the only fibre source on cholesterol serum levels in the rat

Diet	Fibre	Total cholesterol (mg/dL)	HDL-cholesterol (mg/Dl)	LDL-cholesterol (mg/dL)	AI [1]	Triglycerides (mg/dL)	Refer-Ences
16 % olive oil 0,5 % bile salt 1,5 % cholesterol 1,5 % salt solution	Control	569.3±32.4	19.7±1.5	576.6±37.3	29.3±5.1	ND [2]	32
	Sulphated glucurono-Xylorhamnan	385.6±38.4	26.0±5.2	359.4±42.5	13.8±5.3		
	Fucoidan	524.7±28.5	29.0±6.7	490.3±41.6	16.9±6.1		
	Sodium alginate	405.6±28.2	25.4±2.3	380.3±29.2	15.0±2.8		
	Porphyran	456.7±33.2	20.4±1.0	436.3±33.7	21.4±2.7		
	Funoran	381.6±43.3	21.5±1.1	366.3±38.8	16.7±3.5		
	Agar	566.5±45,3	25.0±7.2	495.9±354	18.2±4.9		
5 % olive oil 0,5 % bile salt 1,5 % cholesterol 1,5 % salt solution	Control	387.5±70.1	20.9±3.7	366.6±70.0	18.5±4.8	80.2±5.1	33
	Funoran	265.3±46.6	22.4±4.1	242.9±47.7	11.3±3.4	42.52±5.5	
5% olive oil 0,25% bile salt 0,5 cholesterol	Control	288.0±24.6[a]	13.9±1.6	ND	ND	115.3±11.4	34
	Alginic acid	421.8±12.8b	15.1±1.5			179.1±22.1	
	Na- alginate	290.4±75.2[a]	29.2±7.9			98.0±15.7	
	Ca- alginate	421.1±52.3$_b$	20.1±40			90.6±8.7	
8% lard, 2% corn oil, 1% cholesterol, 4,5 % bile salt	Guluronic acid-rich alginate	215.0±9.0$_a$	35.6±1.8$_a$	ND	5.2±0.3$_a$	ND	19
	Manuronic acid-rich alginate	251.0±1.8$_b$	32.5±1.9$_a$		6.7±0.7$_b$		
	Without fibre	279.0±4.0$_b$	36.9±23$_a$		6.1±0.6$_{ab}$		

[1] Aterogenic index: VLDL-cholesterol + LDL-cholesterol/HDL-cholesterol. [2] Not determined. Vertical values sharing different subscript letters for the same reference study were significantly different ($p<0,05$).

The effects of sodium alginate on the excretion of sterols and nutrients was investigated in six ileostomised humans fed a low-fibre diet with and without a 7.5 g sodium alginate supplement (36). On the average, 95% of the uronic acids derived from alginate was recovered from the ileostomy bag contents. Alginate supplementation increased fat excretion by 140% and decreased bile acid excretion by 12%. Sodium and potassium excretion increased significantly. Increased

fatty acid excretion may be due to the binding or trapping of fatty acids in the gel matrix formed by alginate, which may also cause a reduced bile flow.

Antihypertensive effects

In a study with rats, Ren et al. (32) reported that systolic blood pressure (SBP) of individuals fed diets with funoran, fucoidan, alginate, and porphyran was markedly lower than that of control group animals (Table 6). Other polysaccharides did not influence systolic blood pressure.

In another study, Ren et al. (33) informed that funoran displays a strong antihypertensive effect. Animals fed an algal polysaccharide diet and a sodium diet supplement for 26 days were examined for systolic blood pressure changes. SBP of the group given funoran was markedly lower than that of the control group. SBP of the funoran group decreased significantly (14%). The mechanism responsible may involve the effect of funoran on urine and serum electrolytes, as the urinary excretion rate was 39% higher in the funoran group than in the control group. Moreover, urinary excretion of sodium was enhanced, and the sodium/potassium ratio was also higher in urine of the funoran group than in control group urine. On the other hand, potassium excretion was 38% lower in the funoran group than in the control group. Regarding serum electrolytes, the serum potassium level of the funoran group was 14% higher than that of the control group. The sodium/potassium ratio value was 13% lower in the funoran group than that observed in the control group. However, serum sodium levels of both groups were almost identical. In sum, this study found a significant positive relationship between urinary sodium excretion and SBP, and between the urine sodium/potassium ratio and blood pressure in rats fed funoran.

TABLE 6

Effect of different sources of algal polysaccharides on systolic blood pressure (sbp) in the rat (32)

Diet	Fibre	SBP (mm Hg)		
		Day 0	Day 12	Day 20
	Control	124.3±1.8	156.5±2.6	167.1±2.5
16 % olive oil	Sulphated-			
0,5 % bile salt	Glucuronoxylorhamnan	125.4±2.1	136.7±2.4	156.8±3.3
1,5 % cholesterol	Fucoidan	134.2±2.6	135.4±2.9	140.1±3.1
1,5 % salt	Na-alginate	125.6±1.7	136.3±3.3	141.6±2.4
solution	Porphyran	128.3±2.6	136.1±2.4	153.1±3.6
	Funoran	137.5±1.9	140.4±2.7	132.4±2.8
	Agar	124.5±2.3	144.5±3.5	148.6±4.6

The antihypertensive effect of fibre from the brown alga Ascophyllum nodosum was investigated in slightly hypertensive patients (24). This fibre was mixed with a large quantity of potassium. Systolic blood pressure dropped significantly by the end of the experiment, from 111,5 to 101,4 mm Hg. Urinary excretion of sodium diminished, while that of potassium increased. This study demonstrated that the decrease in SBP was related to reduced intestinal sodium absorption and enhanced intestinal potassium absorption, since fibre binds sodium from the intestinal medium and releases potassium.

Thus, the different conclusions of the antihypertension studies could be related to the different kinds of fibre used, although the different mineral supplements in the diets should also be taken into account.

CONCLUSIONS

In conclusion, algal polysaccharides differ from terrestrial polysaccharides in composition and degree of polymerisation, and study data suggest that they are more effective in lowering cholesterol and blood pressure levels than other fibre sources. Their possible effects on lipid and cholesterol digestion and absorption have been reviewed taking into account their gel formation, faecal bulking and binding capacities and fermentability. Further studies must be carried out to increase our knowledge of algal polysaccharides and to determine their possible role in the prevention and treatment of CHD and other degenerative diseases.

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