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Bioequivalence of encapsulated and microencapsulated fish-oil supplementation

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ABSTRACT

Omega-3 oil from fish can be stabilised against oxidation using a variety of microencapsulation technologies. Complex coacervation has been used and found to be commercially useful for fortifying foods and beverages with long-chain omega-3 containing oils. Here we report a comparative human bioavailability study of microencapsulated omega-3 fish oil and standard fish-oil soft-gel capsules. Phospholipid levels of long-chain omega-3 fatty acids increased equivalently in both subjects groups. Also, triacylglycerol levels were reduced similarly in both groups. These results indicate that omega-3 fatty acids have equivalent bioavailability when delivered as microencapsulated complex coacervates or as soft-gel capsules.

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1. Introduction

Interest in omega-3 fatty acids began over 30 years ago, with the research of Bang and Dyerberg (Bang & Dyerberg, 1973) which revealed that Greenland Eskimos, despite diets that were very high in fat from marine mammals and fish, suffered very low rates of coronary heart disease. The fat these populations consumed contained large amounts of omega-3 fatty acids, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). A further study confirmed this apparent paradox (Dyerberg & Bang, 1979). Since that time, numerous clinical studies and *in vitro* and *in vivo* experiments have confirmed the beneficial effects of omega-3 fatty acids on a variety of disease conditions including neurological benefits (Dyall & Michael-Titus, 2008), anti-depressive effects (Lin & Su, 2007), and cardiovascular benefits (Bays, 2008; GISSI, 1999; Wang et al., 2006). The most notable benefit of omega-3's has been in the area of cardiovascular disease, specifically the prevention of cardiac arrythmia, sudden death from myocardial infarction and lowering of blood triacylglyceride (Wang et al., 2006). In addition to cardiovascular benefits, omega-3 fatty acids have been found to be important for brain health

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Abbreviations: AA, arachidonic acid; BMI, body mass index; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; HDL-C, high density lipoprotein cholesterol; LCL-C, low-density lipoprotein cholesterol; TG, triacylglyceride, VLCL-C, very low-density lipoprotein cholesterol

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in a variety of age groups, disorders and diseases, ranging from infants, to those with attention-deficit hyperactivity disorder (ADHD), dyslexia, depression, schizophrenia and Alzheimer's disease (Dyall & Michael-Titus, 2008; Lin & Su, 2007; Richardson, 2006; Cole et al., 2005). Furthermore, research in the area of the Inflammatory Bowel Diseases, Crohn's and Ulcerative Colitis, has shown promising results following supplementation with fish oil (Lorenz et al., 1989; Aslan & Triadafilopoulos, 1992; Belluzzi et al., 1996; Kim, 1996), as have studies using omega-3 supplements with rheumatoid arthritis patients (Goldberg & Katz, 2007).

The vast amount of research conducted in the area of omega-3's, especially in the area of cardiovascular disease, has resulted in several national and international groups making formal statements to either increase the consumption of omega-3 fatty acids or acknowledge their importance. These include the American Heart Association, the US Food and Drug Administration as well as the International Society for the Study of Fatty Acids and Lipids (ISSFAL). Recommended intake levels for EPA and DHA range from 160 mg to 1.6 g per day (Meyer et al., 2003). However, the typical Western diet provides only about 100–150 mg per day, which is similar in North America, Europe and Australia. Fish is by far the greatest contributor to food sources of EPA and DHA but the Western diet does not include enough oily fish to meet dietary recommendations. This consumption gap can be bridged by enriching food products with fish oil (Holub & Holub, 2004; Kolanowski & Laufenberg, 2006).

A major difficulty in fortifying foods with fish oil containing EPA and DHA is that these polyunsaturated fatty acids are unstable. They readily oxidise in the presence of light and oxygen with the formation of a variety of degradation products. Some of these degradation products are aldehydes that have an unpleasant smell and taste, leading to off-flavors in food products fortified with fish oil. To overcome this problem and keep fish oil oxidatively stable for the shelf-life of a food product, the fish oil can be microencapsulated. There are several methods of microencapsulating fish oil including producing spray-dried emulsions or spray-dried complex coacervates. To be biologically useful these microencapsulated oils need to be bioavailable. The bioavailability of microencapsulated fish oil as delivered by spray-dried emulsions has been shown to be high in animal and human studies (Wallace et al., 2000; Yep et al., 2002). However, spray-dried emulsions tend to have high surface oils levels, low oil content, and poor stability, making their use limited commercially. Recently, a number of food products have been launched that contain microencapsulated fish oil produced as spray-dried complex coacervates (Mattson et al., 2007; Jin et al., 2007). However, the bioavailability of these powders has not been confirmed.

The aims of this study were (i) to investigate the bioavailability of EPA and DHA when delivered as spray-dried complex coacervates, as compared to a soft-gel supplement; and (ii) to investigate the chronic effects of a low dose of EPA and DHA on fasted plasma EPA and DHA status and triacylglycerol levels. We hypothesized that spray-dried complex coacervates containing fish oil would be bioequivalent to soft-gel capsules, and that low dose supplementation would improve plasma EPA and DHA status and impact triacylglycerol levels.

2. Subjects, materials and methods

2.1. *Subjects and experimental design*

In this cross-over study, 14 male subjects between the ages of 30 and 60 were recruited from the Guelph community. Approval for this study was granted by the Human Ethics Committee of the University of Guelph, and written informed consent was obtained from each subject. Anthropometric data including age, height and weight were collected, and a baseline fasting blood sample was drawn. Height and weight of subjects were measured on entry and completion of the study, and are given in Table 1. Participants were instructed to consume their normal diet, but to avoid consumption of fish and fish oil from 7 to 14 days prior to the commencement of the study and for the duration of the study. Subjects were randomly assigned to two groups. Group 1 consumed 4 fish oil capsule containing approximately 2 g of total eicosapentaenoic acid (EPA 20:5$n-3$) and docosahexaenoic acid (DHA 22:6$n-3$), plus a milkshake, for a period of 3 weeks. The second group consumed 5.9 g of microencapsulated fish oil powder containing approximately 2 g of EPA + DHA, added to the milkshake, for a period of 3 weeks.

2.2. *Production of capsules and microencapsulated fish oil*

The oil used in this study was a 30/20 ethyl ester containing 297 mg/g EPA and 218 mg/g DHA. Gelatine-based soft-gel capsules of approximately 1 g were manufactured by standard methods so that each capsule contained 200 mg of DHA and 272 mg of EPA. Four capsules per day therefore delivered 800 mg of DHA and 1088 mg of EPA. The same ethyl ester oil was microencapsulated using complex coacervation, under Good Manufacturing Practices (GMPs) production conditions, to form multi-core microcapsules as previously described (Yan, WO 2004/041251). Briefly, the one-pot complex coacervation process involved a series of controlled steps. Firstly, fish oil was mixed with an aqueous solution of gelatine and polyphosphate to form a microemulsion. The two polymers were neutralized via the formation of a complex coacervate, resulting in coating of the oil droplets and the formation of primary coated particles of 1–5 μM in size. The individually dispersed primary microcapsules aggregated to form the intact multicore microcapsules of 30–70 μm in diameter. An outer shell

Table 1 – Summary of subject anthropometric data on entry and completion of study

Characteristics of subjects	(n = 14)	
	Entry	Completion
Age (years)	46.6 ± 2.8	46.6 ± 2.8
Height (m)	1.78 ± 0.01	1.78 ± 0.01
Weight (kg)	90.7 ± 4.7	91.4 ± 4.7
BMI (kg/m^2)	28.3 ± 1.2	28.6 ± 1.2

Values are reported as means ± SEM. No significant differences between the two groups of subjects at entry into the study were found ($P > 0.05$). There were no significant changes in weight or BMI with the interventions by ANOVA.

formed by cooling and the particles were cross-linked with transglutaminase enzyme. After crosslinking, the slurry was spray-dried converting the wet slurry into dry powder. Each gram of microencapsulated powder was determined to contain 135 mg/g of DHA and 184 mg/g EPA. Therefore, 5.9 g of powder delivered 800 mg of DHA and 1088 mg of EPA, the equivalent of 4 soft-gel capsules.

2.3. Blood collection

The blood after an initial 3-week washout period (day 0; pre-supplementation) and after 21 days of supplementation with either soft-gel or powder (day 21; supplementation) was collected after an overnight fast by antecubital venipuncture into siliconized tubes. The 3-week washout period was repeated

Table 2 – Effects of fish oil capsules and microencapsulated fish oil powder supplementation on serum triacylglycerols and lipoproteins[a]

	Fish oil capsules (n = 14)		Microencapsulated powder (n = 14)	
	Day 0	Day 21	Day 0	Day 21
Triacylglycerols (mmol/L)	2.85 ± 0.57	2.10 ± 0.31[b]	2.68 ± 0.43	1.86 ± 0.33[c]
Triacylglycerol:HDL cholesterol	3.69 ± 0.90	2.34 ± 0.39[b]	3.02 ± 0.48	2.03 ± 0.39[c]

Note: No differences between treatments by ANOVA.
a Means ± SEM.
b Significantly different from fish oil at day 0, $P < 0.05$ (paired t-test).
c Significantly different from microencapsulated powder at day 0, $P < 0.05$ (paired t-test).

Table 3 – Effects of fish oil capsules and omega-3 microencapsulated powder supplementation on serum lipids and lipoproteins[a]

	Fish oil capsules (n = 14)		Microencapsulated powder (n = 14)	
	Day 0	Day 21	Day 0	Day 21
Total cholesterol (mmol/L)	5.40 ± 0.26	5.60 ± 0.29	5.44 ± 0.33	5.61 ± 0.30
HDL cholesterol (mmol/L)	0.86 ± 0.05	0.94 ± 0.04[c]	0.92 ± 0.04	0.96 ± 0.04
LDL cholesterol (mmol/L)	3.46 ± 0.27[b]	3.69 ± 0.27	3.27 ± 0.34[b]	3.79 ± 0.26
NonHDL cholesterol (mmol/L)	4.54 ± 0.25	4.65 ± 0.28	4.52 ± 0.32	4.65 ± 0.30
Total:HDL cholesterol	6.45 ± 0.40	6.01 ± 0.35[c]	6.03 ± 0.44	5.94 ± 0.40
LDL:HDL cholesterol	3.93 ± 0.34[b]	3.93 ± 0.30	3.66 ± 0.44[b]	4.00 ± 0.34

Note: No differences between treatments by ANOVA.
a Means ± SEM.
b n = 12 as triacylglycerols exceeded 5.0 mmol/L for two subjects.
c Significantly different from fish oil at day 0, $P < 0.05$ (paired t-test).

Table 4 – Effects of fish oil capsules and omega-3 microencapsulated powder supplementation on selected fatty acids of serum phospholipid[A]

Fatty acid	Fish oil capsules (n = 14)		Microencapsulated powder (n = 14)	
	Day 0	Day 21	Day 0	Day 21
% by weight of total fatty acids				
20:4n−6 (AA)	9.63 ± 0.52	8.71 ± 0.48[C]	9.84 ± 0.55	9.06 ± 0.51[D]
20:5n−3 (EPA)	0.80 ± 0.09	3.47 ± 0.25[C]	0.81 ± 0.08	3.28 ± 0.28[D]
22:5n−3[B]	1.02 ± 0.06[a]	1.59 ± 0.08[b,C]	1.03 ± 0.07a	1.39 ± 0.06[c,D]
22:6n−3 (DHA)	2.93 ± 0.18	4.97 ± 0.14[C]	2.78 ± 0.16	5.14 ± 0.18[D]
$\sum n-6$	36.3 ± 0.5	31.6 ± 0.5[C]	36.4 ± 0.4	32.4 ± 0.5[D]
$\sum n-3$	5.2 ± 0.3	10.4 ± 0.4[C]	5.1 ± 0.3	10.2 ± 0.4[D]
n−3:n−6 ratio	0.14 ± 0.01	0.33 ± 0.02[C]	0.14 ± 0.01	0.32 ± 0.02[D]
AA:EPA	13.9 ± 1.6	2.7 ± 0.3[C]	13.3 ± 1.1	3.3 ± 0.5[D]
AA:DHA	3.47 ± 0.34	1.77 ± 0.11[C]	3.77 ± 0.35	1.80 ± 0.13[D]
EPA + DHA	3.73 ± 0.24	8.44 ± 0.32[C]	3.58 ± 0.20	8.41 ± 0.40[D]

A Means ± SEM. AA, arachidonic acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid.
B Significant treatment × time interaction, $P < 0.05$ (ANOVA). Values within a row with different alphabetical superscripts are significantly different, $P < 0.05$ (least significant-difference post hoc test).
C Significantly different from fish oil at day 0, $P < 0.05$ (paired t-test).
D Significantly different from microencapsulated powder at day 0, $P < 0.05$ (paired t-test).

followed by the cross-over section of the trial. Those subjects who received encapsulated fish oil in the first arm then received microencapsulated fish oil powder in the this arm for 3 weeks and vice versa. Blood was collected before and after supplementation as before in this cross-over section of the trial. Whole blood was centrifuged at 1250*g* for 15 min to obtain serum. Serum was used for measurement of total cholesterol, high density lipoprotein cholesterol (HDL), triacylglycerol (TAG), low-density lipoprotein cholesterol (LDL) and fatty acid composition of phospholipids. Serum was stored at −70 °C until all samples were collected and thawed just before analysis of lipids.

2.4. Cholesterol and triacylglyceride measurements

Total cholesterol (TC) was measured enzymatically with a diagnostic test (Sigma Diagnostics Procedure No. 352, St. Louis, MO). HDL-C was isolated using a dextran sulphate and magnesium ion solution to precipitate the very low-density lipoprotein–cholesterol (VLCL–C) and LCL–C from the serum sample. The HDL-C fraction was then assayed by an enzymatic assay (Sigma Diagnostics Procedure No. 352-3, St. Louis, MO). TAG was measured enzymatically with a diagnostic test (Sigma Diagnostics Procedure No. 359, St. Louis, MO). LDL-C was calculated using the formula of Friedewald et al. (1972).

Table 5 – Effects of fish oil capsules and omega-3 microencapsulated powder supplementation on fatty acid composition of serum phospholipid[A]

Fatty acid	Fish oil capsules (n = 14)		Microencapsulated powder (n = 14)	
	Day 0	Day 21	Day 0	Day 21
% by weight of total fatty acids				
14:0	0.43 ± 0.03	0.43 ± 0.03	0.42 ± 0.02	0.39 ± 0.03[D]
14:1	0.15 ± 0.01	0.16 ± 0.01	0.16 ± 0.01	0.16 ± 0.02
15:0	0.28 ± 0.02	0.28 ± 0.02	0.28 ± 0.01	0.25 ± 0.02
16:0	27.6 ± 0.3	27.7 ± 0.3	27.4 ± 0.3	27.5 ± 0.4
16:1	0.38 ± 0.04	0.32 ± 0.03[C]	0.37 ± 0.03	0.28 ± 0.03[D]
18:0	13.4 ± 0.3	13.9 ± 0.2[C]	13.8 ± 0.3	13.9 ± 0.3
18:1	12.1 ± 0.5	10.9 ± 0.3[C]	12.4 ± 0.5	10.6 ± 0.3[D]
18:2n−6	22.0 ± 0.8	19.1 ± 0.7[C]	21.7 ± 0.6	19.6 ± 0.6[D]
18:3n−6	0.104 ± 0.013	0.061 ± 0.008[C]	0.118 ± 0.012	0.061 ± 0.007[D]
18:3n−3	0.27 ± 0.02	0.23 ± 0.02	0.27 ± 0.02	0.24 ± 0.02
18:4n−3	0.034 ± 0.007	0.034 ± 0.007	0.048 ± 0.019	0.031 ± 0.010
20:0	0.54 ± 0.03	0.56 ± 0.02	0.56 ± 0.02	0.55 ± 0.02
20:1[B]	0.17 ± 0.01[a]	0.13 ± 0.01[b,C]	0.12 ± 0.01[b]	0.13 ± 0.01[b]
20:2n−6	0.38 ± 0.01	0.34 ± 0.02	0.38 ± 0.02	0.31 ± 0.02[D]
20:3n−6	3.28 ± 0.18	2.67 ± 0.13[C]	3.41 ± 0.20	2.61 ± 0.13[D]
20:4n−6 (AA)	9.63 ± 0.52	8.71 ± 0.48[C]	9.84 ± 0.55	9.06 ± 0.51[D]
20:3n−3	0.008 ± 0.004	0.006 ± 0.003	0.001 ± 0.001	0.007 ± 0.004
20:4n−3	0.13 ± 0.02	0.15 ± 0.01	0.13 ± 0.02	0.15 ± 0.02
20:5n−3 (EPA)	0.80 ± 0.09	3.47 ± 0.25[C]	0.81 ± 0.08	3.28 ± 0.28[D]
22:0	0.97 ± 0.12	0.96 ± 0.10	0.83 ± 0.08	0.93 ± 0.11
22:1	0.084 ± 0.022	0.103 ± 0.018	0.060 ± 0.024	0.047 ± 0.015
22:2n−6	0.001 ± 0.001	0.006 ± 0.002[C]	0.001 ± 0.001	0.001 ± 0.001
22:4n−6	0.70 ± 0.05	0.57 ± 0.05[C]	0.73 ± 0.04	0.64 ± 0.04
22:5n−6	0.16 ± 0.03	0.11 ± 0.02	0.22 ± 0.02	0.12 ± 0.02[D]
22:5n−3[B]	1.02 ± 0.06[a]	1.59 ± 0.08[b], [C]	1.03 ± 0.07[a]	1.39 ± 0.06[c], [D]
22:6n−3 (DHA)	2.93 ± 0.18	4.97 ± 0.14[C]	2.78 ± 0.16	5.14 ± 0.18[D]
24:0	0.87 ± 0.08	0.92 ± 0.10	0.85 ± 0.09	0.95 ± 0.06
24:1	1.49 ± 0.16	1.61 ± 0.14	1.39 ± 0.13	1.71 ± 0.07[D]
SFA	44.1 ± 0.2	44.7 ± 0.1[C]	44.1 ± 0.2	44.5 ± 0.2
MUFA	14.4 ± 0.5	13.2 ± 0.3[C]	14.5 ± 0.4	12.9 ± 0.4[D]
PUFA	41.5 ± 0.5	42.0 ± 0.4	41.4 ± 0.3	42.6 ± 0.3[D]
$\sum n-6$	36.3 ± 0.5	31.6 ± 0.5[C]	36.4 ± 0.4	32.4 ± 0.5[D]
$\sum n-3$	5.2 ± 0.3	10.4 ± 0.4[C]	5.1 ± 0.3	10.2 ± 0.4[D]
n−3:n−6 ratio	0.14 ± 0.01	0.33 ± 0.02[C]	0.14 ± 0.01	0.32 ± 0.02[D]
AA:EPA	13.9 ± 1.6	2.7 ± 0.3[C]	13.3 ± 1.1	3.3 ± 0.5[D]
AA:DHA	3.47 ± 0.34	1.77 ± 0.11[C]	3.77 ± 0.35	1.80 ± 0.13[D]
EPA + DHA	3.73 ± 0.24	8.44 ± 0.32[C]	3.58 ± 0.20	8.41 ± 0.40[D]

Note: 20:1 and DPA responded differently in the FO and MicroEncap treatments.
A Means ± SEM. AA, arachidonic acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid.
B Significant treatment × time interaction, $P < 0.05$ (ANOVA). Values within a row with different alphabetical superscripts are significantly different, $P < 0.05$ (least significant-difference post hoc test).
C Significantly different from fish oil at day 0, $P < 0.05$ (paired *t*-test).
D Significantly different from microencapsulated powder at day 0, $P < 0.05$ (paired *t*-test).

2.5. Statistical analysis

All data were reported as means ± SEM. Phospholipid and NEFA analysis data that were not normally distributed were transformed before analysis in order to reach normality. When observations were missing, least-squared means were calculated so that means could be compared. Split-plot design, including time and treatment as factors, was used in the analyses. Statistical analyses were done using the SAS system (SAS Institute Inc., Cary, NC). Analyses of variance were performed to determine differences between treatment groups. Post hoc analysis was completed by the least significant-difference procedure. Paired *t*-tests were used to determine differences between day 0 and day 21 within a treatment. Significance was set at $P < 0.05$.

3. Results

Table 2 gives the values for fasting serum lipids and lipoproteins at entry and after the 21-day supplementation period. Results from the cross-over 21-day period are combined with those from the first 21-day period for both the fish oil capsule and microencapsulated powder groups, given an n of 14 for each group. Results show the effects of the fish oil capsules compared to the microencapsulated fish oil on group mean serum triacylglycerol (TAG) levels, as well as on the ratio of TAG to HDL-cholesterol. Both the fish oil capsules and the microencapsulated fish oil resulted in statistically significant reductions in mean TAG levels from baseline to day 21, as well as improvement (lowering) of the mean TAG to HDL ratios. The ANOVA (analysis of variance) showed that there was no difference between the effect of the capsules and the microencapsulated fish oil on the above-mentioned parameters. The effects of fish oil capsules compared to microencapsulated fish oil powder on group mean serum total, HDL, LDL and other cholesterol parameters are shown in Table 3. Statistically significant improvements in mean HDL and total to HDL ratios were seen in the fish oil capsule group only, although a trend toward improvement was seen in the microencapsulated powder group. There were no other significant changes in mean cholesterol values from baseline to day 21. Results of the ANOVA showed no significant difference between the two feeding groups.

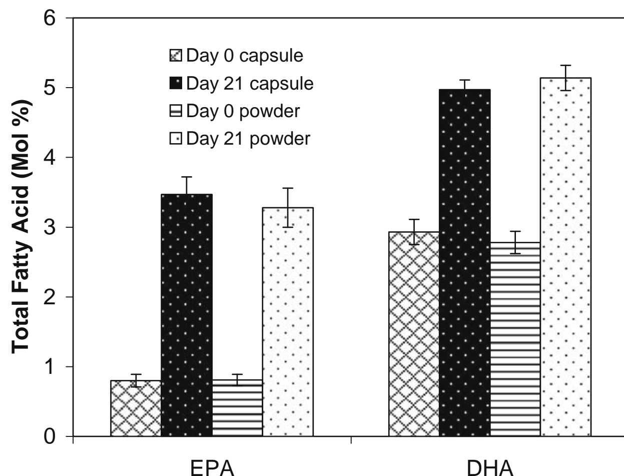

Fig. 1 – EPA and DHA levels in serum phospholipid before and after supplementation in the fish oil capsule group (capsule) and microencapsulated powder group (powder), as mol% of total fatty acids. Note that these data are taken from Table 4.

Table 4 summarizes the results of the effects of the omega-3 capsules and microencapsulated fish oil supplements on selected serum phospholipid fatty acid levels, Table 5 provides a more comprehensive summary of fatty acids (mol%) in the total phospholipid of human serum before and after supplementation with fish oil capsules or microencapsulated fish oil powder. Supplementation with either capsules or microencapsulated fish oil resulted in statistically significant increases in mean serum phospholipid levels of EPA and DHA, from baseline to day 21. EPA rose 434% and DHA rose 170% in the fish oil capsules group, compared with rises of 405% for EPA and 185% for DHA in the microencapsulated fish oil powder group (refer to Fig. 1). This increase was in contrast to the statistically significant reduction in mean serum levels of the omega-6 fatty acid, arachidonic acid (AA), in both feeding groups. AA decreased by 9.6% in the fish oil capsule group and 7.9% in the microencapsulated fish oil powder group. Accordingly, the $n-3$ to $n-6$ ratio was significantly increased in both feeding groups. The capsules and the microencapsulated fish oil powder had no significant difference in effect on phospholipid levels of AA, EPA or DHA. However, significant differences were observed between the two treatments for 20:1 and 22:5$n-3$ (docosapentaenoic acid or DPA). DPA levels rose by 56% in the fish oil capsule group and 35% in the microencapsulated fish oil powder group.

4. Discussion

This study showed that supplementation with either fish oil capsules or microencapsulated fish oil powder produced using complex coacervation significantly reduced triacylglycerols (TAG) after 21 days of treatment. There was no difference in effect between the capsules and the microencapsulated fish oil powder. Many studies have shown that EPA and DHA lower plasma TAG levels. Evidence shows that an elevated TAG level is an important risk factor for cardiovascular disease (CVD) (Graham, 2004). Specifically, elevated post-prandial (following a meal) TAG levels are increasingly acknowledged as an independent predictor of cardiovascular risk. Supplementation with the omega-3 fatty acids EPA and DHA is an effective method of controlling high plasma TG levels, thereby reducing cardiovascular risk.

The ratio of TAG to HDL cholesterol also fell with the supplementation of both fish oil capsules and microencapsulated fish oil powder. The TAG to HDL cholesterol ratio is recognized as a risk factor for CVD, such that an increased ratio increases risk (Volek & Feinman, 2005). This ratio decreases as the TG falls and/or the HDL cholesterol rises. Both the fish oil capsules and the microencapsulated fish oil significantly increased the level of EPA, DPA and DHA in the serum phospholipids when compared to baseline. Importantly, the level of increase in EPA and DHA was not significantly different between the two groups showing equal bioequivalence (Fig. 1).

The ratio of arachidonic acid (AA) to EPA and AA to DHA fell significantly in both groups compared to baseline, while the ratio of $n-3$ to $n-6$ increased significantly when compared to baseline. Long-chain fatty acids, through eicosanoid production, are involved in processes like inflammation, immunoregulation, synaptic modulation and blood flow regulation. Arachidonic acid is the most prominent long-chain PUFA of the omega-6 family and one of the fatty acids from which eicosanoids are produced. The omega-3 and omega-6 LCPUFAs compete for the enzymes involved in eicosanoid production. It is important to maintain a balance of these two families of fatty acids so that eicosanoids derived from EPA are also produced. Diets that provide this balanced omega-6 to omega-3 ratio have been shown to help prevent cardiovascular diseases, improve immune function and alleviate inflammatory conditions.

Microencapsulated fish oil powder produced by complex coacervation is added to a number of food products including bread, yogurt, milk, and infant formula in a number of countries. This study confirms that this form of microencapsulated fish oil is bioavailable and bioequivalent to dietary supplementation with soft-gel capsules.

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