Dietary fish protein alters blood lipid concentrations and hepatic genes involved in cholesterol homeostasis in the rat model

Anjali Shukla, Anja Betziciehe, Frank Hirche, Corinna Brandsch, Gabriele I. Stangl and Klaus Eder*
Institute of Nutritional Sciences, Martin-Luther-University of Halle-Wittenberg, Emil-Abderhalden-Strasse 26, D-06108 Halle/Saale, Germany

(Received 19 January 2006 – Revised 3 May 2006 – Accepted 2 June 2006)

It is known that various dietary plant proteins are capable of influencing the lipid metabolism of human subjects and animals when compared with casein. Less, however, is known about the effects of fish protein on the cholesterol and triacylglycerol metabolism. Therefore, two experiments were conducted in which rats were fed diets containing 200 g of either fish protein, prepared from Alaska pollack fillets, or casein, which served as control, per kilogram, over 20 and 22 d, respectively. As parameters of lipid metabolism, the concentrations of cholesterol and triacylglycerols in the plasma and liver, the faecal excretion of bile acids and the hepatic expression of genes encoding proteins involved in lipid homeostasis were determined. In both experiments, rats fed fish protein had higher concentrations of cholesteryl esters in the liver, a lower concentration of cholesterol in the HDL fraction (p > 1·063 kg/l) and lower plasma triacylglycerol concentrations than rats fed casein (P < 0·05). The gene expression analysis performed in experiment 2 showed that rats fed fish protein had higher relative mRNA concentrations of sterol regulatory element-binding protein (SREBP)-2, 3-hydroxy-3-methylglutaryl coenzyme A reductase, LDL receptor, apo AI, scavenger receptor B1 and lecithin-cholesterol-acyltransferase in their plasma than did rats fed casein (P < 0·05). The faecal excretion of bile acids and the mRNA concentrations of cholesterol 7α-hydroxylase, SREBP-1c and corresponding target genes were not altered. These findings show that fish protein had multiple effects on plasma and liver lipids that were at least in part caused by an altered expression of the hepatic genes involved in lipid homeostasis.

Fish protein: Plasma lipids: Hepatic genes: Rat

A growing body of research offers insight into the influence of different dietary proteins on CVD risk through their impact on blood lipids. For example, plant proteins such as soyabean protein or lupin protein in the diet have been shown to reduce the cholesterol and/or triacylglycerol concentrations of plasma in human subjects (Bakhit et al. 2003; Wergedahl et al. 2004; Ait Yahia et al. 2005) and animals (Sirtori et al. 1998; 2004; Tachibana et al. 2005) when compared with casein. Furthermore, protein isolated from fish fillets also seems to influence blood lipid concentrations in experimental animals (Kritchevsky et al. 1982; Zhang & Beynen, 1993; Wergedahl et al. 2004; Ait Yahia et al. 2005). However, the few studies that have been conducted in this field include conflicting results. Recent studies with rats (Murata et al. 2004; Ait Yahia et al. 2005) and a previous experiment with rabbits (Bergeron et al. 1992) have found a reduction in plasma and VLDL triacylglycerol concentrations in groups fed fish protein compared with groups fed casein and soyabean protein, respectively. Other experiments with rats, however, have not found any effect of fish protein on the concentrations of triacylglycerol in the plasma and VLDL (Ait Yahia et al. 2003; Wergedahl et al. 2004). Additionally, the effects of isolated fish protein on HDL-cholesterol also include conflicting results (Kritchevsky et al. 1982; Zhang & Beynen, 1993; Wergedahl et al. 2004; Ait Yahia et al. 2005), which are suggested to be caused by the different fish protein sources used for the feed studies (Zhang & Beynen, 1993).

To our knowledge, no study has analysed the effects of protein isolated from Alaska pollack fillets on the metabolism of cholesterol and triacylglycerol, although Alaska pollack is widely used for human nutrition. The aim of our first experiment was to investigate the possible effects of a protein isolated from Alaska pollack, compared with casein, on the concentrations of plasma and liver lipids. In order to search for a possible mechanism responsible for the numerous fish protein-induced alterations in lipids in the liver and plasma observed in experiment 1, a second experiment on rats was performed. Rats from experiment 2 were not fasted overnight at the end of the experimental period because overnight fasting leads to a significant downregulation of the genes involved in cholesterol and fatty acid metabolism (see, for example, Horton et al. 1998; Shimano et al. 1999).

The liver is important in maintaining lipid homeostasis, and sterol regulatory element-binding proteins (SREBP) are proteins that regulate the transcription of genes encoding enzymes in the

Abbreviations: ACAT, acyl-CoA: cholesterol acyltransferase; CYP7A1, cholesterol 7α-hydroxylase; GAPDH, glyceraldehyde-3-phosphate-dehydrogenase; HMG-CoA, 3-hydroxy-3-methylglutaryl coenzyme A; LCAT, lecithin-cholesterol acyltransferase; SR-B1, scavenger receptor B1; SREBP, sterol regulatory element-binding protein.

* Corresponding author: Dr K. Eder, fax +49 345 5527124, email klaus.eder@landw.uni-halle.de
biosynthetic pathways of cholesterol and triacylglycerol. To investigate whether the observed effects of fish protein on lipid concentrations in the plasma and liver were induced by an altered activity level of SREBP, the mRNA concentrations of SREBP target genes were determined in a second experiment. To search for a possible mechanism underlying the fish protein-induced increase in cholesterol concentration in the liver, the relative mRNA concentration of SREBP-2 in the liver was determined, together with the mRNA concentrations of its target genes 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase and LDL receptor, the key enzymes required for cholesterol synthesis and cholesterol uptake into cells (Vallett et al. 1996; Horton et al. 2002). Cholesterol homeostasis is achieved by a balance of uptake, biosynthesis, storage, catabolism and export. To gain further insights into cholesterol catabolism, the mRNA concentration of cholesterol 7α-hydroxylase (CYP7A1), the key enzyme in the synthesis of bile acids from cholesterol, and the total amounts of bile acids in the faeces would provide information about the possible effects of fish protein on cholesterol excretion via the bile acids.

The determination of the relative mRNA concentrations of the genes involved in HDL metabolism should provide an insight into the effects observed with fish protein on the HDL fraction in experiment 1. These were apo AI, scavenger receptor B1 (SR-B1) and lecithin-cholesterol acyltransferase (LCAT). Apo AI is one of the two major protein components of HDL and SR-B1, otherwise known as HDL receptor, and serves as a docking platform for the selective uptake of HDL and unloading of the HDL cholesterol in the liver (Acton et al. 1996), whereas the esterification of cholesterol by LCAT is critical for optimal cholesterol uptake and the maturation of HDL (Genest et al. 1999).

The measurement of SREBP-1c, an important determinant of lipogenic gene transcription in the liver (Shimano et al. 1999; Osborne, 2000; Horton et al. 2002), should provide additional information about possible mechanisms by which the fish protein modulates triacylglycerol concentrations in the plasma. Besides the relative mRNA concentration of SREBP-1c, the SREBP-1c-activated target genes such as glucose-6-phosphate dehydrogenase, fatty acid synthase and Δ9-desaturase involved in the de novo synthesis of fatty acids were also determined.

Data obtained from previous studies on the effects of different dietary proteins suggest that alterations in lipid metabolism could be mediated by differences in the amino-acid patterns of the dietary proteins (Ait Yahia et al. 2003; Wergedahl et al. 2004). To search for constituents that could be responsible for the effects of fish protein on circulating cholesterol and triacylglycerol, we measured the concentrations of amino acids in the diets and in the plasma.

Materials and methods

Animals

Two experiments were conducted with a total of forty-eight male Sprague–Dawley rats (twenty-four in each experiment) supplied by Charles River (Sulzfeld, Germany). The rats were randomly assigned to two groups of twelve rats each in each experiment, with an initial body weight of 72 (SD 6) g in experiment 1 and 77 (SD 5) g in experiment 2. Young growing rats were chosen for both experiments according to recent experiments on the effects of fish protein on plasma lipids (Wergedahl et al. 2004; Ait Yahia et al. 2005). For the measurement of plasma lipid concentration, rats from experiment 1 were fasted 12 h before being killed. Rats from experiment 2 were not fasted before being killed because food deprivation before killing leads to a significant downregulation of the genes involved in fatty acid synthesis and cholesterol metabolism, which were to be measured in this study (Horton et al. 1998; Shimano et al. 1999).

All rats were kept individually in Macrolon cages in a room maintained at a temperature of 23°C and 50–60 % relative humidity with lighting from 06.00 to 18.00 hours. All the experimental procedures described followed established guidelines for the care and handling of laboratory animals and were approved by the council of Saxony-Anhalt, Germany.

Experimental diets

All rats were fed a semi-synthetic diet containing 200 g of either casein or fish protein per kilogram. The amount of experimental protein in the diet was chosen according to a recent experiment with rats on the effects of fish protein on blood pressure and lipid metabolism (Ait Yahia et al. 2005). The diets contained the following ingredients (g/kg): fish protein or casein, 200; sucrose, 200; lard, 100; cellulose, 50; corn starch, 390; vitamin and mineral mixture, 60; dl-methionine, 2; cholesterol 0.5. Lard as the type of dietary fat and cholesterol used for the experimental diets were added to the diet not primarily in order to increase the plasma cholesterol concentration but to mimic Western diets, which are commonly rich in saturated fats and cholesterol. Vitamins and minerals were supplemented according to recommendations of the American Institute of Nutrition for rat diets (Reeves et al. 1993).

In both experiments, food intake was controlled. The amount of diet was slightly below that of similar diets consumed ad libitum by rats in preliminary studies. The amount of food offered daily was increased continuously during experiment 1 from 8·0 to 14·0 g and during experiment 2 from 6·0 to 14·0 g. Thus, all rats within one experiment were fed equal amounts of diet daily. The amount of diet was slightly below that consumed ad libitum by the rats and was administered once daily at 08.00 hours. Water was freely available from nipple-drinkers. The experimental diets were fed for 20 d (experiment 1) and 22 d (experiment 2), respectively. The differences between the time schedules of the two experiments were caused by technical reasons.

Preparation and characterisation of the dietary proteins

Fish protein was isolated from fresh Alaska pollack fillets obtained from a local supermarket. After all visible fat and connective tissues had been removed, the fillets were cut into small pieces, boiled for 30 min and then chilled overnight at 4°C. The fish mash was homogenized, freeze-dried and ground. The resulting fish powder was treated twice with acetone and once with acetone–ethanol (1:1, v/v) to remove the protein-associated lipids. After evaporation of the remaining acetone and ethanol, the crude fish protein was ground again and stored at –20°C. Casein was obtained from Meggle (Wasserburg, Germany) and underwent no further processing.
The crude components of the dietary proteins, determined by the official methods of Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten (Naumann & Basler, 1993), are given in Table 1. The concentrations of crude protein and crude ash were similar in both the two proteins. The concentration of crude fat was low in both proteins. The amino acid concentrations of the diets are shown in Table 2, and the fatty acid composition of the diets is shown in Table 3. The fatty acid composition was essentially identical in diets containing casein and diets containing fish protein. Palmitic acid (16:0), stearic acid (18:0), oleic acid (18:1) and linoleic acid (18:2n-6) were quantitatively the most important fatty acids, whereas the concentrations of n-3 fatty acids were low in both types of diet.

**Sample collection**

Rats fasted overnight from experiment 1 and non-fasted rats from experiment 2 were decapitated under light anaesthesia with diethyl ether after overnight fasting. Plasma was separated from heparinised whole blood by centrifugation at 1500g for 10 min at 4°C. Liver was excised, weighed and immediately snap-frozen in liquid N2. Aliquots of liver for RNA isolation were stored at −80°C; other samples were stored at −20°C. During the second week of the experimental period, faeces were collected, dried, weighed and stored at −20°C until analysis.

**Amino acid analysis**

To determine the amino acid concentrations in the diet, samples were oxidised and then hydrolysed with 6 M-HCl (Bassler & Buchholz, 1993). Separation and quantification of the amino acids were performed by ion-exchange chromatography following post-column derivatisation in an amino-acid analyser (Biotronic LC 3000; Eppendorf, Hamburg, Germany). Tryptophan was determined by digesting the diet with Ba(OH)2 (Fontaine et al. 1998). The tryptophan concentration in the diet was measured by reversed-phase HPLC (Eder et al. 2001). The concentrations of free amino acids in the plasma of the rats were measured as isoidole derivatives by HPLC (1100 series; Agilent Technologies, Waldbronn, Germany) according to Schuster (1988) after pre-column derivatisation. Isoindole derivatives were detected at an excitation wavelength of 337 nm and an emission wavelength of 454 nm. Homocysteine and cysteine concentrations were also determined by HPLC (Vester & Rasmussen, 1991).

**Plasma and liver lipids**

Plasma lipoproteins were separated by stepwise ultracentrifugation (Mikro-Ultrazentrifuge; Sorvall Products, Bad Homburg, Germany) at 900 000g at 4°C for 1.5h by appropriate density cuts commonly used for the measure of rat lipoproteins (Sparks et al. 1998; Giudetti et al. 2003; Sirtori et al. 2004). Plasma densities were adjusted by NaCl and KBr, and the lipoprotein fractions ρ < 1.006 kg/l (defined as VLDL in experiment 1 and VLDL plus chylomicrons in experiment 2), 1.006 kg/l < ρ < 1.063 kg/l (defined as LDL) and ρ > 1.063 kg/l (defined as HDL) were removed by suction. Lipids were extracted from liver with a mixture of n-hexane and isopropanol (3:2, v/v; Har & Radin, 1978). For determination of the concentrations of lipids in liver, aliquots of the lipid extracts were dried and the lipids dissolved using Triton X-100 (De Hoff et al. 1978). Concentrations of triacylglycerols and cholesterol in the plasma and lipoproteins and those of liver were determined using enzymatic reagent kits (1-14 830, 1-14 856; VWR International, Darmstadt, Germany). The fractions of free and esterified cholesterol in liver were separated by TLC and determined densitometrically (Hojnacki et al. 1976).

**Faecal bile acids**

The total bile acid content of the faeces of rats in experiment 2 was determined enzymatically (DiaSys Diagnostic Systems, Holzheim, Germany) by a modified method of Marlett & Fischer (2002) using taurocholic acid as a standard. For that purpose, the bile acids were extracted from freeze-dried faeces with ethanol and NaOH as described recently (Dongowski et al. 2002).
Table 3. Concentrations of fatty acids in the diets used in experiments 1 and 2

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Casein diet Experiment 1 (g/kg diet)</th>
<th>Casein diet Experiment 2 (g/kg diet)</th>
<th>Fish protein diet Experiment 1 (g/kg diet)</th>
<th>Fish protein diet Experiment 2 (g/kg diet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:0</td>
<td>25.6</td>
<td>25.3</td>
<td>25.4</td>
<td>25.4</td>
</tr>
<tr>
<td>16:1</td>
<td>2.4</td>
<td>2.3</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>18:0</td>
<td>16.2</td>
<td>15.1</td>
<td>16.0</td>
<td>15.0</td>
</tr>
<tr>
<td>18:1–9</td>
<td>37.4</td>
<td>39.6</td>
<td>37.1</td>
<td>39.3</td>
</tr>
<tr>
<td>18:2–6</td>
<td>10.8</td>
<td>10.4</td>
<td>10.7</td>
<td>10.4</td>
</tr>
<tr>
<td>18:3n-3</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>20:5n-3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>22:6n-3</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Relative mRNA concentrations of hepatic genes

The relative mRNA concentrations of hepatic genes involved in lipid homeostasis were only measured in rats from experiment 2 that were not fasted before decapitation. For analysis of gene expression, total RNA was extracted from frozen liver samples using Trizol reagent (Invitrogen, Karlsruhe, Germany). RNA was quantified by A 260 and its integrity verified by agarose gel electrophoresis using ethidium bromide for visualisation. Total RNA and oligo dT primer (Amersham Pharmacia, Freiburg, Germany) were used for cDNA synthesis (Omniscript RT Kit, Qiagen, Hilden, Germany; Mastercycler Personal, Eppendorf). The concentration of cDNA was analysed by real-time detection PCR (Rotorgene 2000; Corbett Research, Mortlake, Australia) using Sybr Green I (Sigma-Aldrich, Taufkirchen, Germany). The amplification efficiency and the take-off point calculated by the Rotorgene software 4.6 (Corbett Research, Mortlake, Australia) were used for comparative quantification. The expression signal of the housekeeping gene glyceraldehyde-3-phosphate dehydrogenase (GAPDH) served as an internal control for normalisation.

PCR was carried out using 100 μl PCR tubes with a final volume of 15 μl reaction mixture containing 500 μmol/l dNTP (Roth, Karlsruhe, Germany), 3.5 mmol/l MgCl₂, 5 U Taq DNA polymerase and 1.5 μl 10 x buffer (all from Promega, Mannheim, Germany), 0.38 μl 10 x Sybr Green I, 2 μl of the first-strand cDNA and 2 μl of the primer mix (Roth). The primer oligonucleotides were selected using the Primerselect software (DNA-Star Inc., Madison, WI, USA) and theabi-Prism Primerpairs software (Applied Biosystems, Weiterstadt, Germany) from database sequences.

The primer sequences used for RT-PCR were as follows: 5′-GCA-TGG-TCC-GTG-TTC-C-3′ (forward) and 5′-GGG-TGG-TCC-AGG-GTT-TCT-TAC-TC-3′ (reverse) for rat GAPDH (EC 1.2.1.12); 5′-TGC-CCT-CAT-GAC-CGA-CCG-CAA-CTT-3′ (forward) and 5′-GAC-AGG-ACC-AAGAG-GCC-CAT-CTG-3′ (reverse) for rat apo AI; 5′-GGT-TTG-TGT-GCG-CGG-CCT-TTC-TTC-3′ (forward) and 5′-CGA-CGC-CCT-TGA-ATT-TGA-TG-3′ (reverse) for rat SR-B1; 5′-AGG-TTG-CAG-GAC-TGG-TAG-AGG-3′ (forward) and 5′-CAG-GAG-GAA-GTT-GTG-ATT-GTC-3′ (reverse) for rat LRAT (EC 2.3.1.43); 5′-AAG-GGG-CGT-GCA-AAG-ACA-ATC-3′ (forward) and 5′-ATC-CCA-CGC-GAA-AAG-CAT-3′ (reverse) for rat MDM2; 5′-AGC-CTC-GAG-CTG-TGC-CAC-CGG-CAG-GAG-3′ (forward) and 5′-AAC-CGG-CCG-CAT-CG-AGG-CAC-GAG-AAA-G-3′ (reverse) for rat LDL receptor; 5′-CCG-GTA-ATG-ATG-GGC-CAA-GAG-3′ (forward) and 5′-AGG-CGG-GGG-GAG-GCA-TCA-GAA-G-3′ (reverse) for SREBP-2; 5′-CAA-GAC-GCA-CCT-CGC-TAT-CC-3′ (forward) and 5′-CCG-GCA-GGT-CAT-TCA-GTT-G-3′ (reverse) for CYP7A1 (EC 1.14.13.17); 5′-GGC-CTC-TGT-GTC-CCT-GTC-3′ (forward) and 5′-CCC-CTC-GAC-CTT-GGC-TTC-CTA-AG-3′ (reverse) for ACAT-2 (EC 2.3.1.26); 5′-GGA-GGC-ATG-GAT-TGC-ACA-TT-3′ (forward) and 5′-AGG-AAG-GCT-TCC-AGG-GAG-3′ (reverse) for rat SREBP-1c; 5′-CCA-GGC-TCC-ACA-AGC-ACC-CTA-AC-3′ (forward) and 5′-AAT-TAG-CCC-CCA-CGA-CGC-TCC-TCA-GTA-3′ (reverse) for rat glucose-6-phosphate dehydrogenase (EC 1.1.1.49); 5′-CTT-CTT-CCC-TGC-TAG-GTT-CTA-CTT-3′ (forward) and 5′-ACT-CGG-CGG-GAG-GGA-TGC-CCA-CTT-3′ (reverse) for rat fatty acid synthase (EC 2.3.1.85); 5′-CCG-TGG-TTT-TTT-CTT-CTC-3′ (forward) and 5′-CTT-GCC-CTT-CTT-CTC-ATT-3′ (forward) and 5′-CTT-GCC-CTT-CTT-CTC-ATT-3′ (reverse) for rat 3-hydroxysterol desaturase (EC 1.1.49.9).

The cDNA of GAPDH, apo AI, SR-B1, LCAT, HMG-CoA reductase, LDL receptor, SREBP-2, CYP7A1, ACAT, SREBP-1c, glucose-6-phosphate dehydrogenase, fatty acid synthase and 3-hydroxysterol desaturase was amplified in cycles of 20 s denaturation at 95℃, 30 s annealing at an appropriate temperature and 40 s elongation at 72℃. Fluorescence was measured at 72℃. A final melting curve guaranteed the authenticity of the target product.

Statistics

Means of the two groups were compared by Student’s t test for each experiment. Values in the text are means and standard deviations. Means were considered significantly different at P<0.05.

Results

Experiment 1

Food intake throughout the feeding period was the same for each rat, averaging 13.5 g/d. The body weight gains did not differ between the two groups of rats (casein group 6.15 (SD 0.35) g/d, fish protein group 6.10 (SD 0.65) g/d; n 12). Rats fed the fish protein had lower plasma concentrations of homocysteine, serine, histidine, threonine, tyrosine and valine, and higher concentrations of plasma glycine, arginine and taurine than rats fed casein (Table 4). The plasma concentrations of homocysteine, glutamic acid, asparagine, glutamine, alanine, methionine, tryptophan, isoleucine, phenylalanine, leucine, and lysine did not differ between the two groups of rats (Table 4).

Rats fed fish protein had lower concentrations of cholesterol in plasma and HDL (Fig. 1), and a higher ratio of LDL-HDL...
cholesterol than rats fed casein (casein group 0·54 (SD 0·11) mmol/mmol; fish protein group 0·69 (SD 0·17) mmol/mmol; n 12; P<0·05). Concentrations of cholesterol in VLDL and LDL did not differ between the two groups of rats (Fig. 1).

Concentrations of triacylglycerols in plasma, VLDL and HDL were lower in rats fed the fish protein than in rats fed casein (Fig. 2). The concentration of triacylglycerols in the LDL fraction did not differ between the two groups of rats (Fig. 2).

The liver weight/100 g body weight did not differ between the two groups of rats (casein group 3·54 (SD 0·91) g/100 g body weight; fish protein group 3·78 (SD 0·61) g/100 g body weight; n 12). The concentrations of total cholesterol and cholesteryl esters in the liver were higher in rats fed fish protein than in rats fed casein (Fig. 3). The concentration of free cholesterol in the liver did not differ between the two groups of rats (Fig. 3). The concentrations of triacylglycerols in liver were no different between the two groups of rats (Fig. 3).

**Table 4.** Concentrations of amino acids in the plasma of rats fed a diet containing casein or fish protein in experiments 1 and 2 (Mean values and standard deviations for twelve determinations)

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Casein (μmol/l)</th>
<th>Fish protein (μmol/l)</th>
<th>Casein (μmol/l)</th>
<th>Fish protein (μmol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methionine</td>
<td>41 (5)</td>
<td>42 (10)</td>
<td>56 (10)</td>
<td>54 (9)</td>
</tr>
<tr>
<td>Homocysteine</td>
<td>11 (3)</td>
<td>7 (1)*</td>
<td>11 (3)</td>
<td>8 (1)*</td>
</tr>
<tr>
<td>Cysteine</td>
<td>156 (23)</td>
<td>147 (27)</td>
<td>132 (42)</td>
<td>118 (18)</td>
</tr>
<tr>
<td>Taurine</td>
<td>50 (10)</td>
<td>171 (30)*</td>
<td>60 (20)</td>
<td>159 (24)*</td>
</tr>
<tr>
<td>Glycine</td>
<td>246 (25)</td>
<td>354 (53)*</td>
<td>158 (27)</td>
<td>349 (58)*</td>
</tr>
<tr>
<td>Lysine</td>
<td>476 (81)</td>
<td>517 (84)</td>
<td>474 (61)</td>
<td>614 (150)*</td>
</tr>
<tr>
<td>Arginine</td>
<td>112 (18)</td>
<td>146 (22)*</td>
<td>89 (17)</td>
<td>148 (22)*</td>
</tr>
<tr>
<td>Valine</td>
<td>130 (21)</td>
<td>106 (16)*</td>
<td>186 (56)</td>
<td>108 (17)*</td>
</tr>
<tr>
<td>Leucine</td>
<td>105 (17)</td>
<td>94 (17)</td>
<td>119 (32)</td>
<td>86 (19)*</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>67 (11)</td>
<td>68 (12)</td>
<td>83 (20)</td>
<td>70 (11)</td>
</tr>
<tr>
<td>Histidine</td>
<td>51 (8)</td>
<td>41 (6)*</td>
<td>43 (12)</td>
<td>29 (9)*</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>94 (21)</td>
<td>65 (10)*</td>
<td>89 (21)</td>
<td>55 (9)*</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>49 (9)</td>
<td>46 (9)</td>
<td>42 (7)</td>
<td>41 (8)</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>56 (9)</td>
<td>61 (11)</td>
<td>67 (11)</td>
<td>70 (14)</td>
</tr>
<tr>
<td>Threonine</td>
<td>527 (117)</td>
<td>313 (50)*</td>
<td>533 (140)</td>
<td>408 (76)*</td>
</tr>
<tr>
<td>Serine</td>
<td>331 (33)</td>
<td>276 (26)*</td>
<td>276 (37)</td>
<td>258 (30)</td>
</tr>
<tr>
<td>Alanine</td>
<td>351 (67)</td>
<td>464 (197)</td>
<td>533 (61)</td>
<td>566 (134)</td>
</tr>
<tr>
<td>Glutamic acid</td>
<td>121 (27)</td>
<td>125 (16)</td>
<td>93 (12)</td>
<td>95 (17)</td>
</tr>
<tr>
<td>Glutamine</td>
<td>689 (66)</td>
<td>614 (82)</td>
<td>665 (88)</td>
<td>547 (81)*</td>
</tr>
</tbody>
</table>

*Mean values were significantly different from those of rats fed the casein-based diet: Student's t test, P<0·05.

Concentrations of triacylglycerols in plasma, VLDL and HDL were lower in rats fed the fish protein than in rats fed casein (Fig. 2). The concentration of triacylglycerols in the LDL fraction did not differ between the two groups of rats (Fig. 2).

Food intake throughout the feeding period was the same for each rat, averaging 10 g/d. The body weight gains of rats fed fish protein were higher than those of rats fed casein (casein group 5·45 (SD 0·22) g/d; fish protein group 5·97 (SD 0·28) g/d; n 12; P<0·05). Rats fed the fish protein had lower plasma concentrations of homocysteine, histidine, threonine, tyrosine, valine, leucine, glutamine and asparagine, and higher plasma concentrations of glycine, arginine and taurine than rats fed casein (Table 4). The plasma concentrations of cysteine, glutamic acid, alanine, methionine, tryptophan, isoleucine, phenylalanine and lysine were no different between the two groups of rats (Table 4).

Rats fed fish protein had a higher concentration of LDL cholesterol, a lower concentration of HDL cholesterol (Fig. 1) and a higher ratio of LDL:HDL cholesterol than rats fed casein (casein group 0·31 (SD 0·02) mmol/mmol; fish...
Concentrations of cholesterol in the plasma and the triacylglycerol-rich lipoprotein fraction, including VLDL and chylomicrons, did not differ between the two groups of rats (Fig. 1). Rats fed fish protein had lower concentrations of triacylglycerols in their plasma, in the triacylglycerol-rich lipoprotein fraction (VLDL plus chylomicrons), in LDL and in HDL (Fig. 2).

The liver weight per 100 g body weight was lower in rats fed fish protein than in rats fed casein (casein group 4.51 (SD 0.37) g/100 g body weight; fish protein group 4.08 (SD 0.37) g/100 g body weight; n 12; P < 0.05). The concentrations of total cholesterol and cholesteryl esters in the liver were higher in rats fed fish protein than in rats fed casein (Fig. 3). The concentration of the free cholesterol in liver remained unaffected by the diet (Fig. 3). The concentration of triacylglycerol in the liver was no different between the two groups of rats (Fig. 3).

The excretion of bile acids via the faeces did not differ between the two groups of rats (casein group 7.48 (SD 3.78) mmol/d; fish protein group 8.22 (SD 1.99) mmol/d; n 12).

Rats fed fish protein had higher relative mRNA concentrations of apo AI, LCAT and SR-B1 (Fig. 4), and higher relative mRNA concentrations of SREBP-2, HMG-CoA reductase and LDL receptor in the liver (Fig. 5), than did rats fed casein. The relative mRNA concentration of ACAT (casein group 7.48 (SD 3.78) µmol/d; fish protein group 8.22 (SD 1.99) µmol/d; n 12) and the relative gene expression of CYP7A1 (casein group 1.00 (SD 0.56); fish protein group 0.96 (SD 0.67); n 12) were not different between the two groups of rats. The relative mRNA concentration of SREBP-1c (casein group 1.00 (SD 0.56); fish protein group 1.03 (SD 0.53); n 12), and the relative mRNA concentrations of the corresponding downstream genes glucose-6-phosphate dehydrogenase (casein group 1.00 (SD 0.85); fish protein group 1.54 (SD 1.18); n 12), fatty acid synthase (casein group 1.00 (SD 0.98); fish protein group 2.18 (SD 0.67); n 12) were not different between the two groups of rats (Fig. 4).

The concentration of triacylglycerols in the plasma and lipoproteins of rats fed diets containing casein (⌀) or fish protein (●) in (a) experiment 1 and (b) experiment 2. Values are means with their standard deviations shown by vertical bars, for twelve determinations. *Mean values were significantly different from those of rats fed the casein-based diet: Student’s t test, P < 0.05.
Fig. 5. Relative mRNA concentrations of sterol regulatory element-binding protein 2 (SREBP-2), HMG-CoA reductase and LDL receptor in the liver of male rats fed diets containing 200 g/kg casein (●) or fish protein (■) for 22 d (experiment 2). Values were related to the reference gene glyceraldehyde-3-phosphate-dehydrogenase (GAPDH). Values are means with their standard deviations shown by vertical bars, for twelve determinations. *Mean values were significantly different from those of rats fed the casein-based diet (expressed as 100% of casein as control). Student’s t test, P < 0.05.

Discussion
The current experiments on the effects of isolated fish protein from Alaska pollack fillets on the cholesterol and triacylglycerol concentration of lipoproteins and liver, and the genes involved in lipid homeostasis, show a variety of significant fish protein-associated alterations in lipid metabolism. The main effects of the fish protein on cholesterol metabolism compared with casein were an increase in liver cholesterol concentration, a reduction in HDL (p > 1.063 kg/l) and a stimulated gene expression of the genes for apo AI, SREBP-2, HMG-CoA reductase and LDL receptor.

The finding that the relative mRNA concentrations of SREBP-2 and HMG-CoA reductase were higher in rats fed fish protein compared with rats fed casein suggests that cholesterol synthesis might possibly be stimulated by the fish protein, which could in turn be responsible for the observed accumulation of cholesterol in the liver. This assumption is supported by the findings of Wergedahl et al. (2004), who observed a higher activity of HMG-CoA reductase in rats fed fish protein compared with those fed casein, although this effect was observed only in genetically hyperlipidaemic obese Zucker rats but not in normal Wistar rats.

As well as an increase in HMG-CoA reductase expression, mRNA levels of LDL receptor were also increased in rats fed fish protein. Both are target genes of SREBP-2 and indicate an activation of this transcription factor by fish protein. The increase in cholesteryl esters in the livers of rats fed fish protein supports the fact that greater amounts of cellular cholesterol are normally associated with a higher concentration of esterified cholesterol (Field et al. 1987). The failing response of the expression of ACAT, which catalyses the formation of cholesteryl esters from cholesterol and long chain fatty acyl-Co-A, thus modulating the potential toxic effects of excess cholesterol in cell membranes (Chang et al. 1997), is most likely explained by the fact that an enlarged amount of cellular cholesterol stimulates primarily the activity rather than the transcription of ACAT (Chang et al. 2001; Lange et al. 2004). The observed difference in the liver cholesterol concentrations of rats from experiments 1 and 2 can possibly be explained by the differences in the amounts of food that were ingested during experiments 1 and 2.

As hepatic cholesterol homeostasis is achieved by a balance of biosynthesis, storage, catabolism and export, processes that influence cholesterol excretion may have contributed to the observed cholesterol accumulation in the livers of rats fed fish protein. Excess cholesterol is normally eliminated from liver mainly via bile acids and CYP7A1 is the key enzyme of synthesis of bile acids from cholesterol (Vlahoecevic et al. 1999). As the relative mRNA concentration of CYP7A1 in the liver and the amounts of bile acids excreted via the faeces did not, however, differ between the two groups of rats, it is suggested that the cholesterol accumulation in the livers of rats fed fish protein might not be due to a reduced excretion of the cholesterol via the bile acids.

However, despite the observed cholesterol accumulation in the liver of rats fed protein from Alaska pollack, the concentration of cholesterol in the plasma was not increased compared with that in rats fed casein. By measuring the different density fractions in plasma from rats of both experiments, we found a lower cholesterol concentration in the HDL fraction (p > 1.063 kg/l) in those fed fish protein compared with those fed casein. The cut-off chosen for lipoprotein separation was typical for human subjects but also matched that used in previous rat studies (Sparks et al. 1998; Giudetti et al. 2003; Sirtori et al. 2004). This means the 1.006 < p < 1.063 lipoprotein fraction contained, besides IDL, LDL and some HDL particles as well; this may be the reason for the inconsistent effects of fish protein on this density fraction in experiments 1 and 2. A major regulator of circulating LDL-cholesterol is the LDL receptor (Meddings et al. 1986). The higher mRNA concentration of LDL receptor in the liver of rats fed fish protein could have possibly contributed to an increased removal of LDL from the circulation, thereby preventing a distinct LDL accumulation in plasma, albeit with an increased expression of HMG-CoA reductase.

The HDL-lowering effect observed with fish protein feeding is in agreement with recent findings in hyperlipidaemic obese Zucker rats fed fish protein from salmon (Wergedahl et al. 2004). HDL is the principal vehicle for the removal of surplus cholesterol from the peripheral tissues for disposal in the liver. Several genes are involved in HDL metabolism, such as LCAT, critical for optimal cholesterol uptake and maturation of HDL-3 to HDL-2 (Genest et al. 1999), apo AI, a structural component of HDL, and SR-B1, otherwise known as LDL receptor, which is responsible for the selective uptake of HDL. The increased gene expression of LCAT and apo AI would normally contribute to an increase in HDL cholesterol concentration. Although, the reduced concentration of HDL cholesterol observed in the rats fed fish protein could possibly be related to an increased expression of SR-B1, which mediates the selective uptake of HDL-derived lipids into the liver, further investigation is necessary to clarify the mechanisms.

Another remarkable effect of fish protein from Alaska pollack compared with casein was a distinct reduction in the triacylglycerol concentration in the plasma, by about 27% in experiment 1 and 48% in experiment 2. The hypotriacylglycerolaemia
Fish protein and lipid metabolism

primarily resulted from reduced amounts of circulating triacylglycerol-carrying lipoproteins (p < 1·006 kg/l) and confirms other reports on the effects of fish protein in spontaneously hypertensive rats (Ait Yahia et al. 2005), rabbits (Bergeron et al. 1992) and premenopausal women (Gascon et al. 1996). Hypertriacylglycerolaemia could possibly be caused by a diminished synthesis of triacylglycerols in the liver, an increased catabolism of fatty acids or a diminished secretion of triacylglycerols from the liver via VLDL. The measurements of SREBP-1c mRNA concentration, along with the mRNA concentrations of the SREBP-1c target genes such as fatty acid synthase, glucose-6-phosphate dehydrogenase and 9α-desaturase, were not indicative of an inhibition of lipogenesis. Thus, in contrast to SREBP-2, the SREBP-1c-mediated pathway seems not to be altered by fish protein. A former study with rabbits has found a higher lipoprotein lipase activity in animals fed fish protein compared with those fed soybean protein (Bergeron et al. 1992). We therefore suggest that hypotriacylglycerolaemia observed in the rats fed fish protein could be caused by a stimulation of plasma triacylglycerol clearance, although this needs to be proved in a further study.

Studies dealing with the effects of different dietary proteins from plant and animal sources on lipid metabolism suggest that specific amino acids could be responsible for the various effects observed (Kritchevsky et al. 1982; Sugiyama et al. 1986; Morita et al. 1997; Wergedahl et al. 2004). Methionine is assumed to be one of the most important amino acid that contributes to changes in lipid metabolism. Recent data also indicate that dietary methionine exerts its effects on cholesterol metabolism by an elevation of circulating homocysteine, which in turn is suggested to be an activator of the transcription factor SREBP-2 and thereby stimulates the gene expression of cholesterol-synthesising enzyme HMG-CoA reductase (Woo et al. 2005). However, the concentrations of the two amino acids did not differ between the treatment groups and did not provide any explanation for the observed activation of SREBP-2.

In conclusion, the present findings suggest that the fish protein from Alaska pollack exerted distinct effects on plasma and liver lipids, which were, at least in part, caused by an altered expression of the hepatic genes involved in lipid homeostasis.

Acknowledgements

The present study was supported by a grant (0312750A) from the Bundesministerium für Bildung und Forschung.

References


Meddings J, Spady D & Dietzchy J (1986) Kinetic constants for receptor-dependent and receptor-independent low density


