Regulatory potential of $n$-3 fatty acids in immunological and inflammatory processes

H. Grimm$^{1*}$, K. Mayer$^2$, P. Mayser$^3$ and E. Eigenbrodt$^4$

$^1$Department of General and Thoracic Surgery, University of Giessen, Rudolf-Buchheim-Strasse 7, D-35385 Giessen, Germany
$^2$Department of Internal Medicine II, University of Giessen, Klinikstrasse 36, D-35385 Giessen, Germany
$^3$Department of Dermatology and Andrology, University of Giessen, Gaffkystrasse 14, D-35385 Giessen, Germany
$^4$Institute for Biochemistry and Endocrinology, Veterinary Faculty, University of Giessen, Frankfurter Strasse 100, D-35392 Giessen, Germany

Over the last few years immunonutrition has gained increasing importance. Among other compounds lipids, especially $n$-3 polyunsaturated fatty acids, were shown to influence the immune response. The anti-inflammatory effects they exert can be induced by free fatty acids, triglyceride fatty acids, after incorporation into the membrane photospholipid bilayer or following metabolism to eicosanoids. $n$-3 Fatty acids influence inflammatory cell activation processes from signal transduction to protein expression even involving effects at the genomic level. $n$-3 Fatty acid-mediated mechanisms decreased cytokine-induced adhesion molecule expression, thereby reducing inflammatory leucocyte-endothelium interactions and modified lipid mediator synthesis, thus influencing the transendothelial migration of leucocytes and leucocyte trafficking in general. Even the metabolic repertoire of specific immunocompetent cells such as cytokine release or proliferation is modified by $n$-3 fatty acids. Beyond this they regulate lipid homeostasis shifting the metabolic pathways towards energy supply thus optimizing the function of immune cells. Due to the regulatory impact on different processes of inflammatory and immune cell activation $n$-3 fatty acids provide positive effects on various states of immune deficiencies and diseases with a hyperinflammatory character, among which selected examples are presented.

$n$-3 Polyunsaturated fatty acids: Immunonutrition: Inflammation: Immune defence

Introduction

Immunonutrition combining nutrition and pharmacological intervention has become of particular interest over the last few years. Among the different nutrients fat has attracted special attention. As early as 1942 the immunomodulating influence of lipids was published (Tannenbaum, 1942). Later immunological and inflammatory processes have been shown to be influenced by a selective lipid supply and the importance of polyunsaturated fatty acids (PUFA) as essential components in human nutrition has been substantiated. Among these, $n$-3 PUFA, in which the last double-bond is located between the third and fourth carbon atoms from the methyl end of the fatty acid chain, have gained increasing importance. Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are scarce in Western diets but make up an appreciable part of the fat in cold-water fish and seal meat. $n$-3 PUFA have been shown to suppress (Meydani et al. 1991), to have no effect on (Berger et al. 1993) or to increase (Kelley et al. 1988) certain immune functions.

Essentiality and metabolism of $n$-3 fatty acids

Only algae, plants and some fungi are capable of forming $n$-3 fatty acids de novo, since biochemical pathways for $n$-3 fatty acid desaturation are present exclusively in the chloroplasts of these cells. Fish and other marine animals are able to elongate and desaturate these parent essential fatty acids, forming the long-chain $n$-3 PUFA (Simopoulos, 1991). $\alpha$-Linolenic acid serves as substrate for EPA and DHA production in humans. However, man has only a limited capacity of synthesizing EPA from $\alpha$-linolenic acid by desaturation and elongation. Long-term $n$-3 deficiency

Abbreviations: PUFA, polyunsaturated fatty acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; AA, arachidonic acid; PD, prostaglandin; TX, thromboxane; LT, leukotriene; PAF, platelet activating factor; ICAM, intercellular adhesion molecule; TNF, tumour necrosis factor; PPAR, peroxisome proliferator-activated receptor.

* Corresponding author: Dr Helmut Grimm, MD, fax +49 641 99 44709, email helmut.grimm@chiru.med.uni-giessen.de
causes neurological symptoms, retarded growth and skin lesions which are reversible upon n-3 fatty acid supplementation (Connor et al. 1991). In order to increase EPA levels, humans depend on the intake of seafood as the main source of long-chain n-3 fatty acids. Dietary supplementation with n-3 fatty acids was shown to enhance the n-3 to n-6 fatty acid ratio in membrane phospholipids of red blood cells (Brown et al. 1991), granulocytes (Chilton et al. 1993), platelets (Croset et al. 1992), endothelial cells, monocytes, brain cells (Tocher et al. 1991) and hepatocytes (Bourre et al. 1990). EPA and the n-6 arachidonic acid (AA) are competitively metabolized via the cyclooxygenase, lipoxygenase and cytochrome P450 pathways to eicosanoids such as prostaglandins (PG), thromboxanes (TX), leukotrienes (LT), lipoxins and epoxy-compounds. Compared to AA, EPA is the preferential substrate for lipoxigenase which explains for the higher formation of EPA-derived products at the expense of AA-derived metabolites when both free fatty acids are simultaneously available.

### n-3 Fatty acids as precursors of anti-inflammatory eicosanoids

EPA-derived lipid mediators possess markedly reduced inflammatory properties (Lee et al. 1988). TXA3 for example shows reduced proaggregatory and vasoconstrictive properties compared to AA-derived TXA2, while the antiaggregatory and vasodilative efficacy of PG3 equals that of PG2. Thus, predominant prostanoid synthesis from n-3 fatty acids results in reduced proaggregatory and vasodilatoratory effects. Beyond this, it appears that AA-derived PGE2 potently inhibits lymphocyte proliferation at the expense of PG1-2. In order to increase EPA levels, humans depend on the intake of seafood as the main source of long-chain n-3 fatty acids. Dietary supplementation with n-3 fatty acids was shown to enhance the n-3 to n-6 fatty acid ratio in membrane phospholipids of red blood cells (Brown et al. 1991), granulocytes (Chilton et al. 1993), platelets (Croset et al. 1992), endothelial cells, monocytes, brain cells (Tocher et al. 1991) and hepatocytes (Bourre et al. 1990). EPA and the n-6 arachidonic acid (AA) are competitively metabolized via the cyclooxygenase, lipoxygenase and cytochrome P450 pathways to eicosanoids such as prostaglandins (PG), thromboxanes (TX), leukotrienes (LT), lipoxins and epoxy-compounds. Compared to AA, EPA is the preferential substrate for lipoxigenase which explains for the higher formation of EPA-derived products at the expense of AA-derived metabolites when both free fatty acids are simultaneously available.

### n-3 Fatty acids and adhesion molecules

Adhesive interactions between leucocytes and cellular or extracellular components of tissues are involved in inflammatory or immunological response mechanisms. Adhesion molecules direct the leucocyte-endothelium interactions, transendothelial migration of leucocytes and leucocyte trafficking in general (Munro, 1993). In several studies n-3 fatty acids have been shown to influence the expression of adhesion molecules. Culture of human endothelial cells with DHA resulted in a decreased cytokine-induced expression of intercellular adhesion molecule-1 (ICAM-1), vascular cell adhesion molecule-1 (VCAM-1) and E-selectin associated with a reduced adherence to human blood monocytes (DeCaterina & Libby, 1996). In other in vitro experiments DHA inhibited TNF-α-induced expression of VCAM-1 but not ICAM-1 or E-selectin by cultured human endothelial cells (Weber et al. 1995). There are just a few studies dealing with the influence of dietary lipid application on the expression of adhesion molecules. Fish oil supplementation in healthy human volunteers resulted in significantly lower levels of expression of ICAM-1 and leucocyte function antigen-1 on blood monocytes (Hughes et al. 1996).

### Modification of inflammatory cell activation by n-3 fatty acids

n-3 Fatty acids have been shown to influence quite a series of inflammatory processes from signal transduction to protein expression (Fig. 1, Table 1). EPA and DHA compete with LTB4 in receptor occupancy (Yageloff et al. 1995). Receptor-ligand interactions influence the structure of so called G proteins, which play an important role in signal transduction. By replacing GDP with GTP, the subunits of the G proteins dissociate activating phospholipase C. DHA inhibits TNF-α-induced phospholipase C activation (Weber et al. 1995). Phospholipase C triggers the phosphatidylinositol response in the course of signal transduction. During this process diacylglycerol and inositoltrisphosphate are released, activating protein kinase C which then phosphorylates target proteins. EPA and DHA inhibit protein kinase C activation in human lymphocytes (May et al. 1993). AA which is released from membrane phospholipids together with diacylglycerol during signal transduction activates the transcription factor or nuclear factor NFκB, which then translocates into the cell nucleus and induces a number of the inflammatory genes. Fish oil-derived EPA inhibits AA-induced NFκB activation (Camandola et al. 1996). Following gene induction messenger RNA is produced and this process can also be inhibited by n-3 fatty acids (Sellmayer et al. 1996).

n-3 Fatty acids impair proinflammatory cytokine production by human mononuclear cells (Endres et al. 1989) and reduce the expression of adhesion molecules and major histocompatibility complex antigens (DeCaterina & Libby, 1996; Collie-Duguid & Wahle, 1996; Hughes et al. 1996; Pietsch et al. 1995).
Fatty acids and their metabolites regulate transcription factor function through phosphorylation, redox state or proteolytic modification or through binding of an activating ligand by the transcription factor.

**n-3 Fatty acids as fuel partitioners**

*n*-3 PUFA also act as intra- and intercellular fuel partitioners (Fig. 2). They coordinately suppress the expression of lipogenic genes and induce the transcription of genes encoding proteins of lipid oxidation and thermogenesis (Jump & Clarke, 1999; Baillie et al. 1999; Xu et al. 1999). Lipid metabolism is thereby shifted from energy storage to energy supply which is, among other things, important for the optimal function of immune cells. Peroxisome proliferator-activated receptors (PPAR) are a group of key nuclear receptors involved in lipid homeostasis (Forman et al. 1997; Kliewer et al. 1997; Devchand et al. 1996), which have been also identified in lymphoid tissue (Braissant et al. 1996). PPAR are among the family of lipid-activated transcription factors (Clarke et al. 1999). The amino acid sequence of PPAR indicated that they possess structural features characteristic of steroid receptors, i.e. a ligand-binding domain and a zinc finger DNA-binding domain (Isshmann & Green, 1990). PPAR control the process of induction of genes encoding carnitine palmitoyltransferase (Mascaro et al. 1998), mitochondrial HMG-CoA synthase (Rodriguez et al. 1994), peroxisomal acyl-CoA oxidase (Baillie et al. 1999; Jump & Clarke, 1999), fatty acid binding proteins (Kletzien et al. 1992), fatty acid transporter and fatty acyl-CoA synthetase (Martin et al. 1997) and uncoupling protein 3 (Baillie et al. 1999). The rapidity with which PUFA modified gene transcription was consistent with a ligand-mediated event, i.e. a PUFA-binding transcription factor. *n*-3 PUFA have been shown to activate PPAR. Some fatty acids and their metabolites bind specifically to different PPAR isoforms. The EPA-derivative 8-HEPE for example is a potent activator and ligand for PPAR-α and α-linolenic acid, EPA or DHA are ligands for PPAR-α (Forman et al. 1997; Kliwer et al. 1997), PPAR-γ (Forman et al. 1997) and PPAR-δ (Kliwer et al. 1997). Apart from the PUFA their metabolites LT and prostanoids enhanced the interaction of PPAR with its DNA recognition sequence and stimulated gene transcription (Deavergne & Wahli, 1999). PGA 2, B 2, D 2 and 15 deoxy Δ12,14-PGI 2 are activators of PPARα, γ and δ, while PGE 2, F 2α and I 2 do not activate PPAR (Forman et al. 1997; Kliwer et al. 1997). Whereas PUFA and their metabolites upregulate genes of fatty acid oxidation and thermogenesis as ligands for PPARα, they govern lipogenic genes by a PPAR-independent mechanism. Among the lipogenic genes controlled by PUFA are hepatic glucokinase (Jump et al. 1994), pyruvate kinase (Liimatta et al. 1994), pyruvate dehydrogenase (Da Silva et al. 1993), acetyl-CoA carboxylase (Katsurada et al. 1990), fatty acid synthase (Clarke et al. 1990; Xu et al. 1999) and adipocyte fatty acid synthase (Mater et al. 1998).

PUFA control lipogenic gene transcription through...
another family of transcription factors, i.e. sterol regulatory binding proteins (SREBP). SREBP are anchored in the endoplasmic reticulum and nuclear envelope. Upon proteolysis SREBP-1 releases a 68 kDa peptide that translocates to the nucleus (Brown & Goldstein, 1999). The translocation of the mature form of SREBP-1 appears to be inhibited by the amount of PUFA incorporated into the membrane phospholipids (Worgall et al. 1998). Dietary fish oil was shown to correlate with a reduced membrane content of SREBP-1, reducing the nuclear content of 68 kDa SREBP-1 upon stimulation. There is evidence that n-3 PUFA suppress SREBP-1 expression by accelerating the rate of SREBP-1 mRNA decay (Xu et al. 1999).

In summary, n-3 fatty acids improve the energy supply to functionally important cells, including immune cells, since they direct fatty acids away from storage towards oxidation by functioning as ligand activators for PPARα and downregulate lipogenic gene induction by suppressing the expression and nuclear translocation of SREBP-1.

**Fig. 2.** Schematic representation of PUFA-mediated regulation of fuel partitioning. PUFA: polyunsaturated fatty acids, PPAR: peroxisome proliferator activated receptor, MUCPs: mitochondrial uncoupling proteins, SREBP: sterol response element-binding protein, FAS: fatty acid synthase.

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**Table 1.** Modification of cell activation by n-3 fatty acids

<table>
<thead>
<tr>
<th>Substrate supplemented</th>
<th>Type of study</th>
<th>Species</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA, DHA</td>
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<td>pig</td>
<td>direct competition with LTβ in receptor occupancy</td>
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<tr>
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<td>in vitro</td>
<td>human</td>
<td>inhibition of TNF-α-induced cell growth</td>
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<td>in vitro</td>
<td>human</td>
<td>inhibition of AA-induced NF-κB activation</td>
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<tr>
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<td>human</td>
<td>inhibition of AA-induced VCAm1 mRNA</td>
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<tr>
<td>EPA, DHA</td>
<td>in vitro</td>
<td>human</td>
<td>decreased TNF-α, IL-1β, IL-6, and IL-8 mRNA</td>
</tr>
<tr>
<td>EPA, DHA</td>
<td>in vitro</td>
<td>human</td>
<td>decreased mRNA and ICAM-1 expression</td>
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<td>human</td>
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<tr>
<td>EPA, DHA</td>
<td>in vitro</td>
<td>human</td>
<td>decreased expression of CD36</td>
</tr>
</tbody>
</table>

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**References**

Yagaloff et al. 1995

Brown & Goldstein, 1999

Worgall et al. 1998

Xu et al. 1999
Regulatory potential of n-3 polynsaturated fatty acids in clinical and experimental studies

Taking into account their influence on the processes of inflammatory and immune cell function it is not surprising that n-3 fatty acids exert positive effects on different states of immune deficiencies and diseases with a hyperinflammatory character. Here selected examples of inflammatory disorders are presented (sepsis and psoriasis are discussed in detail in separate articles of this supplement).

**Experimental transplantation**

In transplantation research the prolongation of graft survival is accepted as a means of establishing the efficacy of new immunosuppressive drugs. We demonstrated that continuous infusion of a fish oil-based lipid emulsion proved to be immunosuppressive, as indicated by a 50 % prolongation of graft survival in a rat heart allotransplant model (Grimm et al. 1994b). The process of rejection is accompanied by a progressive accumulation of mononuclear cells in the graft with the amount of T-cells, especially T-helper cells characterizing the intensity of the rejection process (Häyry, 1984). In the fish oil-treated rats the number of infiltrating cells, i.e. polymorphonuclear neutrophils and the particularly important CD 4+ and CD 8+ T-cells (Mason & Morris, 1986), was reduced by up to 50 % compared with the controls (Grimm et al. 1995). Decreased graft infiltration coincided with a diminished fraction of T-cells circulating in the peripheral blood, indicating a reduced T-cell recruitment due to fish oil. This traffic of lymphocytes before being trapped in allografts alters the profile of peripheral blood mononuclear cells, which is used clinically for cytotoxicimmunological monitoring (May et al. 1990). Proliferation and graft infiltration of immunocompetent cells depend on cytokine-regulated cell-cell interactions. Mitogen-stimulated TNF-α release by mononuclear cells harvested from fish oil-treated rats was significantly reduced compared with the controls (Grimm et al. 1994a), an effect demonstrated by others upon enteral administration of fish oil (Endres et al. 1989). The observed inhibition of proliferation and graft infiltration of immunocompetent cells in the fish oil group is at least partially explained by the reduced cytokine release by mononuclear cells and the diminished recruitment of T-cells from lymphatic compartments. Furthermore, T-lymphocyte proliferation has been shown to be inhibited in vitro by an increased concentration of free fatty acids via an eicosanoid-independent mechanism (Calder et al. 1992). Interestingly, fish oil infusion led to a 2.5-fold increase in free plasma fatty acid concentration compared to soybean oil-infused controls (Grimminger et al. 1996). Artificial lipid aggregates are known to activate the endothelial lipoprotein lipase, including translocation of this enzyme from its cellular binding sites into the vascular compartment (Peterson et al. 1990). Individual components of the free fatty acid pool might have influenced the rejection process by inhibiting the mobilization of polymorphonuclear granulocytes (PMN). When compared with the n-6 product LTB 4, which mediates adhesion, diapedesis and chemotaxis of PMN (Goetzl & Pickett, 1980), LTB 5 synthesized from free EPA is almost inactive.

Free AA and EPA derived from an intercellular fatty acid exchange among active inflammatory cells (Chauncey et al. 1988) are metabolized to lipid mediators via cooperative eicosanoid synthesis. The considerable increase in free plasma EPA (>30 μmol/l), exceeding by 2-fold free AA concentration, upon fish oil infusion in our model, is assumed to result in a preferential synthesis of 5-series LT by neutrophils stimulated in this natural environment (Grimminger et al. 1992). This causes a shift in LT generation toward EPA-derived products which explains the reduced PMN graft infiltration due to fish oil infusion, since LTB 5 possesses a more than 10-fold reduced chemotactic and PMN-activating capacity as compared with LTB 4 (Leaf & Weber, 1988). Lipid-mediator generation toward EPA-derived products in response to fish oil was even more pronounced in platelets isolated from their plasma compartment. Ex vivo stimulation of these thrombocytes led to an approximately 1:1 release of TXA 3 to TXA 2, which reflects the highest 3-series to 2-series prostanoitid ratio ever reported. By comparison, dietary n-3 fatty acid supplementation for several months resulted in 5-15 % generation of TXB 3 in relation to TXB 2 by human thrombocytes stimulated ex vivo (Fisher & Weber, 1983). Release of the potent vasoconstrictor and platelet aggregator TXA 2 was shown to be increased during acute rejection in experimental transplantation (Foegh, 1988). The considerable shift from TXA 2 to TXA 3 generation following fish oil infusion must be anticipated to have contributed to the prolonged allograft survival, since TXA 3 lacks the prorejection properties of TXA 2 (Leaf & Weber, 1988).

**Experimental lung injury**

In acute and chronic pulmonary inflammation n-3 PUFA have been shown to exert beneficial effects. TXA 2-mediated pulmonary hypertension, vascular leakage and subsequent lung edema induced by cytokines and LT characterize the adult respiratory distress syndrome (Conolly & Repino, 1997), an acute inflammatory lung disorder. In an experimental model of acute lung injury the infusion of free AA caused a marked aggravation of pulmonary edema formation and circulatory disorders due to 4-series LT and 2-series prostanoitid generation (Grimminger et al. 1997). In contrast, vascular leakage was attenuated by the infusion of free EPA paralleled by the generation of 5-series LT. In accordance EPA-rich diets were shown to be organ-protective in different models of septic lung failure or bleomycin-induced lung injury (Mancuso et al. 1997; Murray et al. 1991).

**Rheumatoid arthritis**

This inflammatory disorder with idiopathic etiology involves multiple synovial joints. A reduction of morning stiffness and tender joints was observed in patients upon dietary fish oil supplementation (Kremer, 1996) paralleled by lower serum levels of IL-1β. Fish oil seems to have a beneficial effect in stable rheumatoid arthritis and should be regarded as an adjuvant therapeutic perspective if combined with conventional therapy.
**Inflammatory bowel disease**

Lipid mediators and cytokines are involved in the development of chronic lesions observed in ulcerative colitis and Crohn's disease (Thyssen et al. 1996; Vilaseca et al. 1990). In experimental models fish oil proved to be effective in reducing inflammatory eicosanoid generation and in attenuating organ damage (Campbell et al. 1997). In a rat model intravenous infusion of an α-linolenic acid-rich lipid emulsion decreased LTD 4 generation (Inui et al. 1996a) and reduced the macroscopic damage of the colon wall (Inui et al. 1996b). In accordance with the proposed benefits of n-3 PUFA epidemiological data correlate the increased incidence of Crohn's disease in Japan with an increased ratio of dietary n-6 to n-3 PUFA (Shoda et al. 1996). Enteric-coated fish oil preparations employed in a study on Crohn's disease showed a benefit for high-risk patients in remission in terms of a markedly reduced relapse rate and reduced laboratory indicators of inflammation (Belluzzi et al. 1996).

In ulcerative colitis dietary fish oil was shown to improve the histological findings (Stenson et al. 1992) and to reduce the requirement for anti-inflammatory drugs, including steroids (Aslan & Triadafilopoulos, 1992; Hawthorne et al. 1992). Fish oil proved to be particularly effective as an additive drug in active disease (Hawthorne et al. 1992) and prolonged standard therapy-induced remissions without offering advantages as the sole agent in maintenance therapy (Loeschke et al. 1996). In summary, fish oil might have additive effects in the treatment of ulcerative colitis when taken together with 5-aminosalicylic compounds.

**Concluding remarks**

In the 1970s n-3 fatty acid research was launched with the observation that Greenland Eskimos, a population that consumes large amounts of fatty fish and marine animals, showed a low mortality rate from coronary heart disease (Bang et al. 1971; Kromann & Green, 1980). An increased bleeding time was reported and a lower risk of thrombus formation hypothesized. Meanwhile n-3 fatty acids were demonstrated to influence a series of cellular and molecular processes. They were shown to be metabolized by the same enzymatic pathways as n-6 fatty acids resulting in the production of antithrombotic as well as anti-inflammatory eicosanoids with inhibiting effects particularly on platelets and PMN. Beyond this, n-3 fatty acids once incorporated into membrane phospholipids influence membrane fluidity and the structure of membrane receptors. They are even involved in the process of transmembranal signal transduction and were shown to regulate the activity of various transcription factors thus influencing cell function even at a genomic level. Based on these properties n-3 fatty acids play a role in the regulation of cell surface protein expression, cell-cell interactions, cytokine release and energy supply from lipids. On the basis of these manifold mechanisms it is not astonishing that n-3 fatty acids influence the function of specific and unspecific immune cells and exert beneficial effects in diseases with a hyperinflammatory character. They even turned out to be immunosuppressive in an experimental transplant model. This repertoire of anti-inflammatory and immunosuppressive properties holds further promise that n-3 fatty acids might be integrated as adjunct therapeutic measures in a variety of hyperinflammatory or autoimmune diseases.

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n-3 fatty acids and immune defence


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