Excessive or inappropriate inflammation and immunosuppression are components of the response to surgery, trauma, injury and infection in some individuals and can lead, progressively, to sepsis and septic shock. The hyperinflammation is characterised by the production of inflammatory cytokines, arachidonic acid-derived eicosanoids and other inflammatory mediators, while the immunosuppression is characterised by impairment of antigen presentation and of T-helper lymphocyte type-1 responses. Long-chain \( n-3 \) fatty acids from fish oil decrease the production of inflammatory cytokines and eicosanoids. They act both directly (by replacing arachidonic acid as an eicosanoid substrate and by inhibiting arachidonic acid metabolism) and indirectly (by altering the expression of inflammatory genes through effects on transcription factor activation). Thus, long-chain \( n-3 \) fatty acids are potentially useful anti-inflammatory agents and may be of benefit in patients at risk of hyperinflammation and sepsis. As a consequence, an emerging application for \( n-3 \) fatty acids, in which they may be added to parenteral (or enteral) formulas, is in surgical or critically-ill patients. Parenteral nutrition that includes \( n-3 \) fatty acids appears to preserve immune function better than standard formulas and appears to diminish the extent of the inflammatory response. Studies to date are suggestive of clinical benefits from these approaches, especially in patients post surgery, although evidence of clinical benefit in patients with sepsis is emerging.

Fish oil: Inflammation: Immune function: Parenteral nutrition: Sepsis

**Alterations in the inflammatory and immune responses occur as part of the host response to insult**

The body’s response to insults such as infection, surgery and injury includes an activation of some components of the immune system. The result is the local release of chemical mediators and the appearance of increased concentrations of some of these mediators in the bloodstream. The mediators released include eicosanoids, cytokines, reactive oxygen (superoxide anions, \( \text{H}_2\text{O}_2 \)) and nitrogen (NO) species and platelet-activating factor; collectively, these mediators are known as inflammatory mediators and the process that produces them is termed the inflammatory response. Some of the inflammatory mediators are involved in direct destruction of pathogens, while others play a regulatory role within the immune or whole-body responses to insult (Fig. 1). The overall aims of the inflammatory response appear to be the creation of an environment characterised by oxidative stress and inflammation that is hostile to pathogens and the initiation of cellular immune responses involved in pathogen elimination (Fig. 1). Some components of the inflammatory response, such as IL-1\( \beta \), induce cell-mediated immunity through the activation of T lymphocytes. Although the inflammatory response has evolved to be protective and is clearly essential for host defence against pathogens, the host can be damaged by inappropriate, excessive or untimely production of inflammatory mediators. The body possesses antioxidant defences and is able to produce anti-inflammatory mediators in order to counter excessive oxidative stress and inflammation. Nevertheless, the balance between those conditions that are favourable for the host and those that are damaging to the host is critical.
to the host and those that are not favourable to the host can be lost, and this imbalance can have a major impact on patient outcome. The uncontrolled inflammatory response to insult (e.g. surgery, trauma, burns) is termed the systemic inflammatory response syndrome and involves excessive production of inflammatory cytokines, particularly TNF-α, IL-1β, IL-6 and IL-8 (Bone et al. 1997). Sepsis is the presence of systemic inflammatory response syndrome in response to, or in combination with, an infection (Bone et al. 1997). The mortality risk of sepsis is about 20%, and it predisposes to organ failure, which carries an elevated mortality risk. Septic shock is the occurrence of multiple organ failures, metabolic acidosis and hypotension, and it carries a mortality risk of 40–80% (Bone et al. 1997). Together systemic inflammatory response syndrome, sepsis and septic shock are termed ‘septic syndromes’, and they are the leading cause of death in critically-ill patients in Western countries. In the USA it has been estimated that in 1995 there were >750,000 cases of sepsis, with a 28.6% mortality rate (215,000 deaths) and a total cost of approximately US$ 17 × 10^9 (Angus et al. 2001).

Animal studies suggest a central role for inflammatory cytokines in the septic response. Mice injected with bacterial endotoxin (also termed lipopolysaccharide) exhibit high circulating concentrations of TNF-α, IL-1β, IL-6 and IL-8, and survival of these animals can be improved by administering anti-cytokine antibodies (Beutler et al. 1985; Tracey et al. 1987), cytokine receptor antagonists (Alexander et al. 1991) or anti-inflammatory cytokines such as IL-10 (Marchant et al. 1994), or by knocking out the TNF-α receptor (Pfeffer et al. 1993). Patients with sepsis show markedly elevated circulating concentrations of TNF-α, TNF receptor 1, IL-1β and IL-6, and the patients with the highest concentrations are more likely to die (Girardin et al. 1988; Arnalich et al. 2000; Hatherill et al. 2000). In addition, circulating leucocytes from patients with sepsis have high levels of activated NF-κB, a transcription factor that promotes the expression of numerous genes associated with inflammation, and again levels of activated NF-κB are higher in those patients who go on to die (Arnalich et al. 2000). Although Vervloet et al. (1998) state that ‘these mediators [i.e. inflammatory cytokines] are largely, if not completely, responsible for the clinical signs and symptoms of the septic response to bacterial infection’, other mediators are involved in the pathological processes that accompany critical illness. For example, prostaglandin (PG) E₂ is implicated in sepsis.
burns and critical illness (Grbic et al. 1991; Ertel et al. 1992), while leukotriene (LT) B\(_4\) and oxidants released by neutrophils are involved in acute respiratory distress syndrome (Kollef & Schuster, 1995).

In addition to hyperinflammation, patients with sepsis also display immunosuppression (Meakins et al. 1977; Lederer et al. 1999; Oberholzer et al. 2001). Lymphocytes from patients with sepsis, burns or trauma show impaired proliferation and produce low levels of the T-helper 1-type cytokines (e.g. interferon-\(\gamma\)) associated with host defence against bacteria and viruses, but high levels of the T-helper 2-type and regulatory T-cell-type cytokines (IL-4, IL-10) associated with inhibition of the host defence against bacteria and viruses (O’Sullivan et al. 1995; Heidecke et al. 1999; Lederer et al. 1999; Pellegrini et al. 2000). There also appears to be decreased monocyte expression of human leucocyte antigens (the proteins involved in antigen presentation to T-cells; Hershman et al. 1990; Wakefield et al. 1993; Astiz et al. 1996; Manjuck et al. 2000), which is associated with impaired ability of monocytes to stimulate T-cells (Manjuck et al. 2000). The traditional view is that the immunosuppressed phase of sepsis lags behind the hyperinflammatory phase (Fig. 2), i.e. initially, sepsis is characterised by increased generation of inflammatory mediators, but as it persists there is a shift towards an anti-inflammatory immunosuppressed state. TGF, transforming growth factor. (Modified from Calder, 2004, with permission from the American Oil Chemists’ Society.)

**Fig. 2.** Hypothetical biphasic immuno-inflammatory response to a traumatic insult. In sepsis the immunosuppressed phase lags behind the hyperinflammatory phase, i.e. initially, sepsis is characterised by increased generation of inflammatory mediators, but as it persists there is a shift towards an anti-inflammatory immunosuppressed state. TGF, transforming growth factor. (Modified from Calder, 2004, with permission from the American Oil Chemists’ Society.)

**n-6 PUFA, inflammation and immunity**

Human immune and inflammatory cells are rich in PUFA, especially the n-6 PUFA linoleic acid and arachidonic acid, which together comprise about 30% of the fatty acids present (Gibney & Hunter, 1993; Yaqoob et al. 2000). Cell-culture-based studies with human endothelial cells have suggested that linoleic acid may play a role in inflammation through activation of NF-\(\kappa\)B and increased production of TNF-\(\alpha\), IL-6 and other inflammatory mediators (Hennig et al. 1996, 2000; Toborek et al. 1997, 2002; Young et al. 1998; Park et al. 2001; Dichtl et al. 2002). Arachidonic acid also activates NF-\(\kappa\)B in a monocytic cell line (Camandola et al. 1996), and induces TNF-\(\alpha\), IL-1\(\alpha\) and IL-1\(\beta\) in osteoblasts (Priante et al. 2002) and IL-6 in macrophages (Bagga et al. 2003) and osteoblasts (Bordin et al. 2003). Arachidonic acid is also the principal substrate for cyclooxygenase and lipoxygenase enzymes, giving rise to 2-series PG and thromboxanes (TX) or 5-hydroxyeicosatetraenoic acids and 4-series LT respectively. These mediators, especially PGE\(_2\) and the 4-series LT, have well-recognised roles in inflammation and immunity (Kinsella et al. 1990; Lewis et al. 1990; Tilley et al. 2001). For example, PGE\(_2\) induces fever, increases vascular permeability and causes pain.

LTB\(_4\) increases vascular permeability, is a potent leucocyte chemoattractant, induces release of lysosomal enzymes and reactive oxygen species by neutrophils and induces production of TNF-\(\alpha\), IL-1\(\beta\) and IL-6. Arachidonic acid-derived mediators thus contribute to the inflammatory process and these roles most likely underpin their association with critical illness (Grbic et al. 1991; Ertel et al. 2002; Kollef & Schuster, 1995). Studies using the isolated perfused rabbit lung have identified key pathological roles for arachidonic acid-derived eicosanoids. Infusion of *Escherichia coli* haemolysin causes hypertension mediated by TXB\(_2\) and increases vascular leakage mediated by 4-series LT (Grimminger et al. 1997a). Inclusion of arachidonic acid in the perfusate increases TXB\(_2\) and 4-series LT generation and increases arterial pressure and vascular leakage (Grimminger et al. 1997a,b).

In addition to contributing to inflammatory processes PGE\(_2\) acts to suppress cell-mediated immunity through the inhibition of both T-lymphocyte proliferation (Calder et al. 1992) and the production of the T-helper 1-type cytokines IL-2 and interferon-\(\gamma\) (Betz & Fox, 1991; Snijdewint et al. 1993; Katamura et al. 1995; Hilkens et al. 1996; Miles et al. 2003).

Thus, it is possible that an excessive supply of n-6 PUFA could act to promote, or at least exacerbate, states of inflammation and of immunosuppression. This situation could occur particularly in patients who are critically ill, have suffered a traumatic insult or burns, or have undergone major surgery, since such patients are at risk of developing systemic inflammatory response syndrome and compensatory anti-inflammatory response syndrome. Parenteral nutrition may be indicated for these categories of patient, particularly if the gastrointestinal tract is not fully functional. Lipids were introduced into parenteral nutrition formulas in the 1960s in order to provide a more balanced supply of energy, along with glucose (Edgren & Wretlind, 1963; Hallberg et al. 1966; Wretlind, 1972). The lipid typically used in parenteral nutrition is soya bean oil, in which linoleic acid comprises about 30% of the fatty acids present. A meta-analysis of total parenteral nutrition has suggested that the inclusion of lipids might be detrimental (lipids \(v\). no lipids, \(P=0.09\); Heyland et al. 1998), at least in very-ill patients; in most of the studies included in the meta-analysis soya bean oil-based lipid emulsions were used. A recent study in patients following major
gastrointestinal surgery (Koch & Heller, 2005) has identified that the amount of n-6 PUFA infused is one of two predictors of the length of hospital stay (which increases by 1.6 d/100 g n-6 PUFA infused), the other predictor is the delay in the onset of initiating nutritional support. Some in vitro experiments have shown that soyabean oil-based lipid emulsions can exert immunosuppressive effects (for references, see Calder et al. 1994), which would clearly be detrimental in patients at risk of infection and sepsis. Clinical trials with soyabean oil-based lipid emulsions provide conflicting evidence, with some showing selective immunosuppressive effects (Monson et al. 1988; Battistella et al. 1997; Furukawa et al. 2002), perhaps linked to poorer patient outcomes (Battistella et al. 1997). However, other studies do not show such effects on the immune system (Dionigi et al. 1985; Gogos et al. 1990; Sedman et al. 1991) or on clinical outcomes (Lensske et al. 1998). Details of these studies are given in Table 1. Nevertheless, there is a view developing that the use of lipid emulsions based entirely on soyabean oil in parenteral nutrition may not be optimal or may even be harmful. The concern about potential harm, the view of sepsis as a hyperinflammatory and immunosuppressive' has led to the development of alternative lipid emulsions for parenteral applications. Two approaches to decreasing the amount of linoleic acid present in the emulsion have been to partly replace soyabean oil with triacylglycerols rich in medium-chain saturated fatty acids (termed medium-chain triglycerides; MCT) or with olive oil. These approaches will not be discussed further here, but further information may be found elsewhere (Ulrich et al. 1996; Adolph, 1999).

**Fish oil, inflammation and immunity**

The use of MCT or olive oil in parenteral nutrition results in decreased linoleic acid administration. However, there is a view that n-6 PUFA:n-3 PUFA in lipid emulsions should be decreased (Furst & Kuhn, 2000; Adolph, 2001; Grimble, 2005; Grimm, 2005), and this objective is not achieved with MCT or olive oil since neither of these components contains major amounts of n-3 PUFA. Using fish oil, which contains the long-chain n-3 PUFA EPA and DHA, to partly replace soyabean oil offers the possibility of decreasing both the amount of linoleic acid present and the n-6 PUFA:n-3 PUFA of lipid emulsions. This option is especially attractive because not only is the supply of linoleic acid decreased, but the long-chain n-3 PUFA are themselves anti-inflammatory (for reviews, see Calder, 2001a,b, 2002, 2003, 2005). Consumption of fish oil results in increased amounts of EPA and DHA, partly at the expense of arachidonic acid, in cells involved in immunity and inflammation (see Calder, 2001a). The functional importance of this outcome is that it decreases the amount of arachidonic acid available as a substrate for eicosanoid synthesis. In addition, EPA and DHA competitively inhibit the metabolism of arachidonic acid by cyclooxygenase and 5-lipoxygenase. Through these actions fish oil supplementation of the human diet has been shown to result in decreased production of PGE2, TXB2, LTE4, 5-hydroxyeicosatetraenoic acid and LTE5 by inflammatory cells (Lee et al. 1985; Endres et al. 1989; Meydani et al. 1993; Sperling et al. 1993; von Schacky et al. 1993; Caughey et al. 1996; Treble et al. 2003b). EPA can also act as a substrate for cyclooxygenase and lipoxygenase enzymes, giving rise to a different family of eicosanoids, i.e. the 3-series PG and TX, the 5-series LT and the hydroxyeicosapentaenoic acids. Thus, fish oil supplementation of the human diet has been shown to result in increased production of LTB4, LTE4 and 5-hydroxy-eicosapentaenoic acid by inflammatory cells (Lee et al. 1985; Sperling et al. 1993; von Schacky et al. 1993), although generation of PGE3 has been more difficult to demonstrate (Hawkes et al. 1991). The mediators formed from EPA are frequently less potent than those formed from arachidonic acid. For example, LTB4 is 10-fold to 100-fold less potent as a neutrophil chemoattractant than LTB4 (Goldman et al. 1983; Lee et al. 1984, 1988). A recent study (Bagga et al. 2003) has reported that PGE3 is less potent than PGE2 at inducing cyclooxygenase-2 gene expression in fibroblasts and IL-6 production by macrophages. Studies using the isolated rabbit lung perfused with *E. coli* haemolysin (Grimminger et al. 1997a,b) have identified contrasting effects of arachidonic acid- and EPA-derived eicosanoids. While arachidonic acid infusion increases TXB2 and 4-series LT generation, arterial pressure and vascular leakage (Grimminger et al. 1997a,b), the inclusion of EPA in the perfusate decreases TXB2 and 4-series LT generation, decreases arterial pressure and vascular leakage, and increases the generation of TXB3 and 5-series LT (Grimminger et al. 1997a). Perfusion with fish oil also attenuates the hypertension (Breil et al. 1996) and the increased vascular permeability and oedema (Koch et al. 1995) induced by Ca ionophore. These effects are associated with decreased production of LTC4 and TXB2 and markedly increased production of LTC4 (Koch et al. 1995; Breil et al. 1996).

In addition to the modulation of eicosanoid generation from arachidonic acid and to EPA acting as a substrate for an alternative family of eicosanoids, recent studies (for reviews, see Serhan 2004, 2005) have identified a novel group of anti-inflammatory mediators, termed resolvins, formed from EPA and DHA.

n-3 PUFA from fish oil have also been shown to alter the production of inflammatory cytokines. EPA does not activate NF-κB in a monocyte cell line (Camandola et al. 1996), while both EPA and DHA inhibit endotoxin-stimulated production of IL-6 and IL-8 by cultured human endothelial cells (de Caterina et al. 1994; Khalfoun et al. 1997). More recent studies have shown that: (1) EPA does not induce TNF-α, IL-1α or IL-1β (Priante et al. 2002) or IL-6 (Bordin et al. 2003) in osteoblasts, and even counters the up regulating effect of arachidonic acid (Priante et al. 2002); (2) EPA and DHA can totally abolish cytokine-induced up-regulation of TNF-α, IL-1α and IL-1β in cultured bovine chondrocytes and in human osteoarthritic cartilage explants (Curtis et al. 2000, 2002); (3) EPA or fish oil inhibit endotoxin-induced TNF-α production by monocytes (Lo et al. 1999; Babcock et al. 2002; Novak

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Table 1. Some reported immunological and clinical outcomes of studies using lipid emulsions based entirely on soyabean oil

<table>
<thead>
<tr>
<th>Patient characteristics</th>
<th>Parenteral nutrition used</th>
<th>Duration</th>
<th>Immuno-inflammatory and clinical outcomes measured</th>
<th>Effects observed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undernourished patients undergoing surgery for gastric or oesophageal cancer</td>
<td>No lipid v. soyabean oil</td>
<td>Daily for 2 weeks before surgery and then for 1 week after surgery</td>
<td>Nos. of blood granulocytes, lymphocytes, T-cells and B-cells</td>
<td>Granulocyte nos. increased at week 3 in soyabean oil group; total lymphocytes decreased (approximately 50%) at week 3 in the no-lipid group</td>
<td>Dionigi et al. (1985)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Serum IgG and IgM concentrations</td>
<td>None</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Leucocyte chemotaxis</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Granulocyte adherence to nylon</td>
<td>Decreased (approximately 30%) at week 3 in the no-lipid group</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Granulocyte phagocytosis</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Natural killer cell activity of PBMNC</td>
<td>Decreased (approximately 50%) at day 7</td>
<td>Monson et al. (1988)</td>
</tr>
<tr>
<td>Malnourished patients undergoing surgery for gastrointestinal cancer</td>
<td>Soyabean oil</td>
<td>For 7d before surgery</td>
<td>Nos. of blood T-cell, helper T-cell, suppressor T-cell</td>
<td>Helper : suppressor cells decreased (approximately 20%) in the soyabean oil group</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nos. of blood natural killer cells</td>
<td>Absolute no. and percentage of natural killer cells decreased (approximately 5–10%) in the no-lipid group</td>
</tr>
<tr>
<td>Malnourished seriously-ill patients</td>
<td>No lipid v. soyabean oil; Soyabean oil v. MCT–soyabean oil (50:50, v/v)</td>
<td>10 d</td>
<td>Nos. of blood granulocytes, lymphocytes, T-cells and B-cells</td>
<td>Helper : suppressor cells decreased (approximately 20%) in the soyabean oil group</td>
<td>Gogos et al. (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Serum IgG and IgM concentrations</td>
<td>None</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Leucocyte chemotaxis</td>
<td>None</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Granulocyte adherence to nylon</td>
<td>Decreased (approximately 50%)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Granulocyte phagocytosis</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Natural killer cell activity of PBMNC</td>
<td>Increased (approximately 30%)</td>
<td>Sedman et al. (1991)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T-cell proliferation in response to mitogen</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>IL-2 production by T-cells in response to mitogen</td>
<td>Decreased (approximately 10%) in the no-lipid group; increased (approximately 35%) in the soyabean oil group</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cytotoxicity of IL-2 activated PBMNC</td>
<td>Decreased (approximately 35%) in the soyabean oil group; increased (approximately 15%) in the MCT–soyabean oil group</td>
<td></td>
</tr>
<tr>
<td>Malnourished patients undergoing surgery for gastrointestinal cancer</td>
<td>No lipid v. soyabean oil v. MCT–soyabean oil (50:50, v/v)</td>
<td>For 7d before surgery</td>
<td>Natural killer cell activity of PBMNC</td>
<td>Increased (approximately 30%) in the MCT–soyabean oil group</td>
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<td></td>
<td></td>
<td></td>
<td>T-cell proliferation in response to mitogen</td>
<td>None</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>IL-2 production by T-cells in response to mitogen</td>
<td>Decreased (approximately 10%) in the no-lipid group; increased (approximately 35%) in the soyabean oil group</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cytotoxicity of IL-2 activated PBMNC</td>
<td>Decreased (approximately 35%) in the soyabean oil group; increased (approximately 15%) in the MCT–soyabean oil group</td>
<td></td>
</tr>
<tr>
<td>Trauma patients</td>
<td>No lipid v. soyabean oil</td>
<td>10 d</td>
<td>Natural killer cell activity of PBMNC</td>
<td>Lower (approximately 65%) in the soyabean oil group</td>
<td>Battistella et al. (1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Period on mechanical ventilation</td>
<td>Longer in the soyabean oil group (27 v. 15 d)</td>
<td></td>
</tr>
</tbody>
</table>
et al. 2003; Zhao et al. 2004). EPA is also less potent than arachidonic acid in inducing IL-6 expression by macrophages (Bagga et al. 2003). EPA prevents NF-κB activation by TNF-α in cultured pancreatic cells; an effect that involves decreased degradation of the inhibitory subunit of NF-κB, perhaps through decreased phosphorylation (Ross et al. 1999). Similarly, EPA or fish oil decrease endotoxin-induced activation of NF-κB in human monocytes (Lo et al. 1999; Novak et al. 2003; Zhao et al. 2004), which is associated with decreased phosphorylation of inhibitory subunit of NF-κB (Novak et al. 2003; Zhao et al. 2004), perhaps because of decreased activation of mitogen-activated protein kinases (Lo et al. 2000). These observations suggest direct effects of long-chain n-3 PUFA on inflammatory gene expression via inhibition of activation of the transcription factor NF-κB.

Animal feeding studies with fish oil support the observations made in cell culture in relation to the effects of long-chain n-3 PUFA on NF-κB activation and inflammatory cytokine production. Compared with feeding maize oil, fish oil lowers NF-κB activation in endotoxin-activated murine spleen lymphocytes (Xi et al. 2001). Feeding fish oil to mice decreases ex vivo production of TNF-α, IL-1β and IL-6 by endotoxin-stimulated macrophages (Billiar et al. 1988; Renier et al. 1993; Yaqoob & Calder, 1995) and decreases circulating TNF-α, IL-1β and IL-6 concentrations in mice injected with endotoxin (Sadeghi et al. 1999). Several studies in healthy human volunteers involving supplementation of the diet with fish oil have demonstrated decreased production of TNF-α, IL-1β and IL-6 by endotoxin-stimulated monocytes or mononuclear cells (a mixture of lymphocytes and monocytes; Endres et al. 1989; Meydani et al. 1991; Abbate et al. 1996; Caughey et al. 1996; Treble et al. 2003a; Wallace et al. 2003).

Thus, an examination of fatty acid composition and eicosanoid profiles, cell- and tissue-culture work and animal and human feeding studies has revealed a range of anti-inflammatory actions of long-chain n-3 PUFA (Table 2). These anti-inflammatory actions may be of benefit in sepsis, particularly during the ‘early’ hyperinflammatory phase. The benefits of fish oil in animal models of experimental endotoxaemia have been clearly demonstrated. For example, dietary fish oil or fish oil infused intravenously markedly enhances the survival of guinea-pigs to intraperitoneal endotoxin when compared with safflower oil (Mascioli et al. 1988, 1989). Also, dietary fish oil results in a decreased concentration of circulating post-endotoxin eicosanoids (PGE₂, TXB₂, 6-keto-PGF₁α) in rats and in decreased eicosanoid generation by alveolar macrophages (Utsunomiya et al. 1994; Sane et al. 2000). Furthermore, compared with dietary safflower oil, fish oil results in lower circulating TNF-α, IL-1β and IL-6 concentrations following endotoxin administration to mice (Sadeghi et al. 1999). Dietary fish oil also decreases sensitivity to exogenously-administered inflammatory cytokines (Pomposelli et al. 1990; Mulrooney & Grimble, 1993). Fish oil decreases endotoxin-induced metabolic perturbations in guinea-pigs and rats (Pomposelli et al. 1991; Teo et al. 1991), improves heart and lung function and decreases lung oedema in endotoxins (Mancuso...
**Table 2. Summary of the anti-inflammatory effects of long chain n-3 PUFA (modified from Calder, 2004, with permission from the American Oil Chemists’ Society)**

<table>
<thead>
<tr>
<th>Anti-inflammatory effect</th>
<th>Mechanism(s) involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased generation of arachidonic acid-derived eicosanoids (many with inflammatory actions)</td>
<td>Partial replacement of arachidonic acid in cell membrane phospholipids</td>
</tr>
<tr>
<td></td>
<td>Inhibition of arachidonic acid metabolism by phospholipase A2</td>
</tr>
<tr>
<td></td>
<td>COX and 5-LOX</td>
</tr>
<tr>
<td></td>
<td>Decreased induction of COX-2, 5-LOX and 5-LOX activating protein</td>
</tr>
<tr>
<td></td>
<td>Increased cell membrane phospholipid content of EPA</td>
</tr>
<tr>
<td>Increased generation of EPA-derived eicosanoids (many with less inflammatory actions than those derived from arachidonic acid)</td>
<td>Increased cell membrane phospholipid content of EPA and DHA</td>
</tr>
<tr>
<td>Increased generation of EPA- and DHA-derived resolvins (with anti-inflammatory actions)</td>
<td>Decreased activation of NF-κB (via decreased phosphorylation of IκB)</td>
</tr>
<tr>
<td>Decreased generation of inflammatory cytokines (TNF-α, IL-1β, IL-6, IL-8)</td>
<td>?Altered activity of other transcription factors*</td>
</tr>
<tr>
<td>Decreased expression of adhesion molecules*</td>
<td>?Differential effects arachidonic acid v. EPA</td>
</tr>
<tr>
<td></td>
<td>?Differential effects of arachidonic acid-derived eicosanoids v. EPA-derived eicosanoids</td>
</tr>
<tr>
<td></td>
<td>Decreased activation of NF-κB (via decreased phosphorylation of IκB)</td>
</tr>
<tr>
<td></td>
<td>?Altered activity of other transcription factors</td>
</tr>
</tbody>
</table>

COX, cyclooxygenase; LOX, lipoxygenase; IκB, inhibitory subunit of NF-κB.

*Not discussed here (see Calder, 2002).


In addition to the effects on the production of inflammatory eicosanoids and inflammatory cytokines, long-chain n-3 PUFA also exert effects on cell-mediated immunity. Large amounts of fish oil in the diet of laboratory animals have been reported to exert immunosuppressive effects (for reviews, see Calder, 2001b; Calder et al. 2002). Clearly, such effects are to be avoided in patients with sepsis. However, studies in healthy human volunteers are equivocal, although recent human studies suggest that adverse immunological effects are not exerted at modest doses of fish oil (Yaqoob et al. 2000; Wallace et al. 2003; Miles et al. 2004) and one study reports that enhanced T-cell responses (proliferation and interferon-γ production) may occur at modest doses provided that antioxidants are also given (Treble et al. 2003b). In terms of sepsis, the true test of immunocompetence occurs when live pathogens are administered. This situation is different from using endotoxin, which is not living and therefore does not require a robust cell-mediated immune response to eliminate it. As indicated earlier, it is clear that long-chain n-3 PUFA protect against the deleterious effects of endotoxins, and the same applies to be true for some live pathogens. The infusion of fish oil into rats also receiving low-dose endotoxin decreases the number of viable bacteria in mesenteric lymph nodes and the liver, and as fish oil does not decrease bacterial translocation across the gut, the conclusion drawn is that fish oil must have improved bacterial killing (Pscheidt et al. 2000). Compared with linoleic acid-rich vegetable oils, fish oil fed to rats before exposure to live bacteria (either as a result of caecal ligation and puncture or intravenous administration of live group B Streptococcus) results in increased survival, which is associated with decreased production of PGE₂ (Barton et al. 1991; Rayon et al. 1997). The infusion of fish oil after the induction of sepsis by caecal ligation and puncture decreases mortality (and PGE₂ production) when compared with vegetable oil (Lanza-Jacoby et al. 2001). Intragastric administration of fish oil into chow-fed rats before caecal ligation and puncture improves survival when compared with saline (9 g NaCl/l) or vegetable oil infusion (Johnson et al. 1993). Thus, the picture that emerges from a range of animal studies is that administration of long-chain n-3 PUFA in the form of fish oil increases survival on exposure to live pathogens. From this outcome it can be inferred that host immune defences are likely to have been improved by long-chain n-3 PUFA. Interestingly, several studies have focused on the fish oil-induced decrease in PGE₂ production as being a key mechanistic effect, suggesting that the immunosuppressive effect of PGE₂ generated in response to infection might be deleterious to host survival.

**Use of fish oil in parenteral nutrition**

Lipid emulsions that include fish oil have been used in clinical trials and some of these emulsions have subsequently become commercially available, at least in some countries. Omegaven®, produced by Fresenius Kabi (Bad Homberg, Germany), is a lipid emulsion (100 g lipid/l) that uses fish oil as the lipid source. Each 100 ml Omegaven® contains 2.7–5.9 g EPA + DHA (information supplied by the manufacturers). It is recommended that Omegaven® is used in combination with other emulsions (e.g. those based on soyabean oil or mixtures of MCT and soyabean oil) such that Omegaven® contributes 10–20% of the infused emulsion. SMOF Lipid® is also produced by Fresenius Kabi. It is a lipid emulsion (200 g lipid/l) in which the lipid is a mix of (g/100 g): 30, MCT; 30, soyabean oil; 25, olive oil; 15, fish oil. Lipoplus® (also known as Lipidem®) is also available.

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in some countries), produced by B. Braun (Melsungen, Germany), is a lipid emulsion (200 g lipid/l) in which the lipid is a mix of (g/100 g): 50, MCT; 40, soyabean oil; 10, fish oil. Each 100 ml Lipoplus® contains 0.9–1.7 g EPA + DHA (information supplied by the manufacturers).

**Studies in surgical patients**

Intravenous infusion of a lipid emulsion containing fish oil into patients for 5 d following gastrointestinal surgery results in an altered fatty acid composition of leucocytes; EPA content is increased 2.5-fold (Morlion et al. 1996). This change would be expected to impact on the profile of eicosanoids produced from arachidonic acid and EPA. Indeed, several studies have demonstrated that intravenous infusion of lipid emulsions containing fish oil into patients who have undergone major gastrointestinal surgery results in lower production of arachidonic acid-derived LT (e.g. LTB₄, LTC₄) and TX (e.g. TXA₂) and higher production of EPA-derived LT (e.g. LTB₄, LTB₃-isomers, LTC₄) by blood leucocytes stimulated ex vivo (Morlion et al. 1996; Wachtler et al. 1997; Schulzki et al. 1999; Kelbel et al. 2002; Koller et al. 2003). Plasma TNF-α concentrations are lower at day 6 post surgery while plasma IL-6 concentrations are lower at day 10 post surgery in patients who have undergone major gastrointestinal surgery and then received a mix of MCT–soyabean oil–fish oil (50:30:20, by vol.; a prototype version of Lipoplus®) for 5 d post surgery compared with those who have received a MCT–soyabean oil mix (50:50, v/v; Wachtler et al. 1997). The study does not report clinical outcomes. A more recent study (Weiss et al. 2002) has infused Omegaven®, providing 10 g lipid (fish oil)/d, on the day before abdominal surgery and on days 1–5 following abdominal surgery. On days 4 and 5 the patients also received standard total parenteral nutrition that included 50 g fat as soyabean oil/d. It was found that TNF-α production by endotoxin-stimulated whole blood has a tendency to be lower (although not significantly) at post-operative day 5 in the fish oil group. Serum IL-6 concentrations were reported to be significantly lower at days 0, 1 and 3 in the fish oil group than in the controls. Monocyte expression of human leucocyte antigen-DR was shown to be preserved in the fish oil group, but to decline at post-surgery days 3 and 5 in the control group. No differences in infection rates or mortality were observed, although there was a tendency for post-operative stay in intensive care (4.1 d v. 9.1 d in the control group) and total hospital stay (17.8 d v. 23.5 d in the control group) to be shorter in the fish oil group. Post-operative stay on medical wards was found to be significantly shorter in the fish oil group (P<0.05). Another study (Schauder et al. 2002) has compared the effects of lipid-free total parenteral nutrition and parenteral nutrition including soyabean oil or a soyabean oil–fish oil mix (83:17, v/v; Omegaven®) for 5 d after large-bowel surgery. No differences between the groups were found in relation to the numbers of circulating lymphocytes, B lymphocytes, helper T lymphocytes, cytotoxic T lymphocytes or natural killer cells before surgery or at days 3 and 6 post surgery, although the numbers were affected by surgery itself. No differences between groups were found in relation to T-lymphocyte proliferation, but in the fish oil group IL-2 production was shown to be increased and the post-surgery decline in interferon-γ production prevented. Taken together, these studies indicate that the inclusion of fish oil in parenteral nutrition regimens for patients who have undergone gastrointestinal surgery modulates the generation of inflammatory eicosanoids (Morlion et al. 1996; Wachtler et al. 1997; Koller et al. 2003) and cytokines (Wachtler et al. 1997; Weiss et al. 2002) and may help to counter the surgery-induced decline in antigen-presenting cell activity (Weiss et al. 2002) and T-lymphocyte cytokine production (Schauder et al. 2002). Importantly, these studies do not reveal deleterious immunological effects of fish oil infusion in these patients. Furthermore, the only one of these fairly small studies to have examined hard end points such as length of hospital stay suggests real clinical benefit from fish oil infusion in these patients (Weiss et al. 2002). A more recent report (Tsekos et al. 2004) from a larger cohort of patients receiving parenteral nutrition post surgery does indicate the benefit of the inclusion of fish oil in the regimen. No differences were found between the control group (MCT–soyabean oil; 50:50, v/v) and the patients receiving fish oil (a mix of Omegaven® with the MCT–soyabean oil mix (50:50, v/v) such that a maximum of one-third of the mix was as fish oil) in relation to the percentage of patients who were reported to develop wound infections (6 for the fish oil group v. 11 for the control group) or who subsequently died (12 for the fish oil group v. 15 for the control group), or in the length of hospital stay (25 d for the fish oil group v. 29 d for the control group). However, the percentage of patients in the fish oil group who were readmitted to intensive care (5) was found to be significantly lower (P<0.05) than that for the control group (17). A group of patients also received the fish oil-containing emulsion for 2 d pre-operatively. For this group a number of very significant benefits were found when compared with the control group: a significantly decreased need for mechanical ventilation (17% v. 31% respectively; P<0.05); a significantly shorter length of hospital stay (22 d v. 29 d respectively; P<0.05); significantly less need for readmission to intensive care (5% v. 17% respectively; P<0.05); a significantly lower mortality (3% v. 15% respectively; P<0.05; Tsekos et al. 2004). Another study (Heller et al. 2004) has revealed that intravenous infusion of a lipid emulsion containing soyabean oil–fish oil (80:20, v/v) into patients for 5 d following major gastrointestinal surgery accelerates normalisation of liver and pancreatic function compared with soyabean oil alone. Overall, no difference was found between the groups in relation to the length of stay in the intensive care unit or in hospital. However, in a subgroup of patients at risk of sepsis a reduced intensive care unit stay was reported in the patients receiving fish oil (4.0 d v. 5.3 d in the control group; P=0.01; Heller et al. 2004). In a recently published study (Koch & Heller, 2005) a mixed group of >650 patients, including about 230 post-surgery patients, received parenteral nutrition containing fish oil (Omegaven®) at 0.11 g/kg body weight per d for at least 3 d (mean 8.7 d). A significantly lower rate of infections (P<0.0005), fewer complications (P<0.005) and shorter...
length of hospital stay ($P=0.05$) were reported for the post-surgery patients receiving fish oil compared with those receiving the control emulsion. Furthermore, infusion of about 0.15 g fish oil/kg body weight per d was found to decrease mean intensive care unit stay from 8.7 d to 5.3 d and hospital stay from 27.4 d to 25.5 d. Schulzki et al. (1999) have reported that infusion of a mix of MCT–soyabean oil–olive oil–fish oil (30:30:25:15, by vol.; SMOF Lipid®) into patients on days 1–6 following surgery results in a significantly lower ($P<0.05$) length of hospital stay (13.4 d) compared with patients receiving soyabean oil (20.4 d). In a study by Kelbel et al. (2002) post-surgery patients received soyabean oil or a soyabean oil–fish oil mix (80:20, v/v) for 5 d. It was found that the incidence of sepsis (14% vs. 25% in the control group), deaths in the intensive care unit (7% vs. 12.5% in the control group), the length of intensive care unit stay (2 d vs. 5.5 d in the control group) and the length of hospital stay (18 d vs. 23 d in the control group) have a tendency to be lower in the patients receiving fish oil, although the decrease is not significant. Wichmann et al. (2004) have reported the length of hospital stay for patients who after gastrointestinal surgery received a control emulsion (soyabean oil) or an emulsion that included MCT–soyabean oil–fish oil (50:40:10, by vol.; Lipoplus®). The length of stay was found to be significantly shorter ($P=0.006$) in patients receiving fish oil (17.2 d) than in the control group (21.9 d). Although the studies of Schulzki et al. (1999), Kelbel et al. (2002) and Wichmann et al. (2004) are encouraging, they have been published only in abstract form and further details of these studies are required for them to be evaluated more fully. Even without these details, findings available from published studies in patients undergoing gastrointestinal surgery clearly demonstrate clinical benefit from the inclusion of long-chain n-3 PUFA in parenteral nutrition regimens (Weiss et al. 2002; Heller et al. 2004; Tsekos et al. 2004; Koch & Heller, 2005). However, the study of Tsekos et al. (2004) also demonstrates a much greater benefit if the fatty acids are additionally provided pre-surgery, which is only possible in elective surgery. The greater benefit of pre-operative infusion of long-chain n-3 PUFA may relate to better incorporation of the fatty acids into leucocytes and other tissues.

**Studies in patients with established sepsis**

Infusion of a mix of soyabean oil–fish oil (Omegaven®; 66:33, v/v) over 5 d has been shown to decrease serum C-reactive protein concentration by an average of about 88% in patients with abdominal sepsis; parenteral soyabean oil alone was not found to alter C-reactive protein concentration (Grecu et al. 2003). In patients with sepsis who were intolerant of enteral nutrition and received a standard soyabean oil-based emulsion or an emulsion containing fish oil (Omegaven®) for 5 d (Mayer et al. 2003a) or 10 d (Mayer et al. 2003b) it was found that blood leucocyte counts and serum C-reactive protein concentration tend to be lower and production of LTb4 by stimulated neutrophils is higher in patients receiving fish oil (Mayer et al. 2003a). Production of TNF-α, IL-1β, IL-6, IL-8 and IL-10 by endotoxin-stimulated mononuclear cells does not increase during infusion of the fish oil-containing emulsion, whereas production of the four proinflammatory cytokines is markedly elevated during the first 2 d of infusion of soyabean oil (Mayer et al. 2003b). These studies establish that infusion of long-chain n-3 PUFA into patients with sepsis can modulate inflammatory mediator production and related inflammatory processes. It has been demonstrated that this outcome might be associated with clinical improvements. Grecu et al. (2003) have reported significantly decreased re-operation rates (7% vs. 31% in the control group), intensive care unit stay (3 d vs. 9 d in the control group) and hospital stay (12 d vs. 20 d in the control group) in patients receiving parenteral fish oil (soyabean oil–Omegaven® mix; 66:33, v/v) compared with those receiving soyabean oil, although no difference in mortality was found between the two groups (7–8% in both groups). Koch & Heller (2005), in their study of parenteral n-3 PUFA infusion that included 268 patients with abdominal sepsis, have reported a lower rate of infection and shorter lengths of intensive care unit and hospital stay in those patients receiving >0.05 g fish oil/kg body weight per d than in those receiving <0.05 g fish oil/kg body weight per d. Mortality was found to be significantly decreased in those patients who received >1 g fish oil/kg body weight per d (Koch & Heller, 2005). Thus, these recent data are strongly suggestive of genuine clinical benefit from the inclusion of long-chain n-3 PUFA in parenteral nutrition regimens given to patients with sepsis.

One study that should be mentioned in this context is a study of enteral nutrition in patients with acute respiratory distress syndrome (Gadik et al. 1999), since this study also demonstrates clinical improvement following long-chain n-3 PUFA administration. In this study the control group of patients received an enteral formula in which the lipid source was maize oil–soyabean lecithin (97:3, v/v). The experimental formula was (% v/v): 32, rapeseed oil; 25, MCT; 20, borago (Borago officinalis) oil; 20, fish oil; 3, soyabean lecithin. The experimental formula also contained more vitamin C and vitamin E than the control and it contained β-carotene, taurine and carnitine, which the control formula did not. Patients given the experimental formula for 6 d received (g/d) approximately: 7, EPA; 3, DHA; 6, γ-linolenic acid; 1-1, vitamin C; 0-4, vitamin E; 6-6 mg, β-carotene. By day 4 the numbers of total leucocytes and of neutrophils in the alveolar fluid were found to have declined markedly in the experimental group and to be lower than those in the control group. Arterial oxygenation and gas exchange were shown to have improved in patients in the experimental group, who had a decreased requirement for supplemental O2, decreased time on ventilation support and a shorter length of stay in intensive care (12.8 d vs. 17.5 d in the control group; $P=0.016$). It was found that total length of hospital stay tended to be shorter in the experimental group (29.6 d vs. 34.6 d in the control group; $P=0.07$) and fewer patients developed new organ failure (four of fifty-one patients vs. thirteen of forty-seven patients in the control group; $P=0.015$). Mortality was reported to be 12% in the experimental group and 19% in the control group, although this difference was not significant ($P=0.31$).

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More recently, new data from this study have become available (Pacht et al. 2003). Patients receiving the experimental formula were reported to have lower concentrations of IL-8 in their alveolar fluid and a tendency to lower concentrations of LTB4 and TNF-α. It is possible that the lower concentrations of LTB4 and IL-8, both of which are potent leucocytes chemotactants, may have been responsible for the lower neutrophil infiltration reported in the experimental group, and indeed an association was found between neutrophil counts and these concentrations. This study establishes that the experimental treatment decreases production of inflammatory mediators and infiltration of inflammatory leucocytes and that this outcome can result in marked clinical improvement in extremely-ill patients. As there are many differences in composition between the experimental and control formulas used it is not possible to ascribe the effects and benefits to any particular nutrient. However, the effects on LTB4, IL-8 and TNF-α concentrations are consistent with the effects of long-chain n-3 PUFA reported elsewhere and so it is tempting to ascribe the observed effects to n-3 PUFA.

Conclusions
The response to surgery and to traumatic insults may involve excessive inflammation and an immunosuppressed state in some patients. n-6 PUFA may play a role in creating this state, and approaches to decrease the amount of linoleic acid used in parenteral lipid emulsions are being sought. One approach is to partly replace soyabean oil with fish oil in such emulsions. Long-chain n-3 PUFA from fish oil decrease the production of inflammatory eicosanoids and cytokines. They act both directly (by replacing arachidonic acid as an eicosanoid substrate and by inhibiting arachidonic acid metabolism) and indirectly (by altering the expression of inflammatory genes through effects on transcription factor activation). Thus, long-chain n-3 PUFA are potentially-useful anti-inflammatory agents and may be of benefit in patients at risk of developing a hyper-inflammatory state and sepsis. An emerging application of n-3 PUFA is in patients undergoing surgery or in critically-ill patients; here they may be added to parenteral (or enteral) formulas. Parenteral nutrition that includes n-3 PUFA appears to preserve immune function better than standard formulas and to partly prevent some aspects of the inflammatory response. Studies to date are suggestive of clinical benefits from this approach, especially in patients who have undergone surgery, although evidence of clinical benefit in patients with sepsis is emerging.

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