Abstract
The palliative treatment of patients with advanced pancreatic cancer (APC) has undergone little advancement in the last 15 years. Novel therapies that have been investigated to extend survival have shown little benefit over existing chemotherapy regimens. Patients with APC often experience significant weight loss, which is one of the primary factors involved in declining quality of life. Recently, the ability of $n$-3 fatty acid rich oral preparations to attenuate or reverse tumour-related weight loss has been investigated in this patient group with encouraging results. Laboratory investigation has also yielded promising results suggesting a potential direct tumouricidal effect of $n$-3 fatty acids as well as the putative potentiation of existing chemotherapy regimes. The present review aims to examine the potential applications of fish oils rich in $n$-3 fatty acids in patients with APC, present a selection of the studies carried out to date and outline avenues of possible further clinical investigation.

Key words: $n$-3 Fatty acids: Fish oil: EPA: DHA: Pancreatic cancer


Abbreviations: APC, advanced pancreatic cancer; QOL, quality of life.

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The capacity of human metabolism to derive EPA and DHA by the elongation and desaturation of α-linolenic acid is negligible. Furthermore, this synthesis of longer-chain, n-3 fatty acids from linolenic acid is competitively slowed by n-6 analogues. Therefore, their concentration in tissues is enhanced when they are directly ingested or when competing amounts of n-6 fatty acids are relatively small.

Methods

A PubMed/Medline search of ‘cell proliferation’ OR ‘pancreatic cancer’ AND ‘omega 3’ OR ‘n-3 polyunsaturated fatty acids’ OR ‘EPA’ OR ‘DHA’ was carried out, and relevant articles were screened manually for inclusion in order to provide a representative selection of the important studies carried out to date. The articles were divided into those that utilised pre-clinical in vitro or in vivo work to determine the action of n-3 fatty acids on cell lines or xenograft models and those that used oral preparations of n-3 fatty acids in clinical trials (Tables 1 and 2).

Laboratory studies of n-3 fatty acids in pancreatic cancer models

Both DHA and EHA have been shown to have beneficial effects on pancreatic adenocarcinoma cell lines in vitro.

Table 1. Pre-clinical studies using n-3 fatty acids in neoplastic and proliferative cell lines and xenograft models

<table>
<thead>
<tr>
<th>Study (year)</th>
<th>Model used</th>
<th>Parameters measured and outcome</th>
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<tbody>
<tr>
<td>Falconer et al. (1996)</td>
<td>PC cell lines + different FA</td>
<td>Reduction in cell numbers, viability and proliferation with EPA</td>
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<tr>
<td>Lai et al. (1996)</td>
<td>PC cell lines + EPA</td>
<td>Decrease in cell count and viability mediated by cell cycle arrest and apoptosis with EPA</td>
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<tr>
<td>Ravichandran et al. (2000)</td>
<td>PC cell lines/mouse xenograft + EPA + GLA</td>
<td>Growth inhibition in cell lines with EPA + GLA but no effect in xenograft model</td>
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<tr>
<td>Merendino et al. (2003, 2005)</td>
<td>PC cell lines + butyric acid, DHA or ALA</td>
<td>Reduced cell growth and induction of apoptosis, probably by glutathione depletion, with DHA</td>
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<tr>
<td>Shirato et al. (2005)</td>
<td>PC cell lines + EPA</td>
<td>Dose-dependent inhibition of proliferation + induction of apoptosis with EPA</td>
</tr>
<tr>
<td>Zhang et al. (2007)</td>
<td>PC cell lines + EPA or DHA</td>
<td>Growth and proliferation inhibition with induction of apoptosis with EPA or DHA</td>
</tr>
<tr>
<td>Hering et al. (2007)</td>
<td>PC cell lines + n-3 FA/n-6 FA + gemcitabine</td>
<td>Inhibition of proliferation in n-3 FA group regardless of gemcitabine. Inhibition of NF-κB activation and restoration of apoptosis in gemcitabine-resistant cells with n-3 FA</td>
</tr>
<tr>
<td>Dekoji et al. (2007)</td>
<td>PC cell lines + n-3 FA or n-6 FA</td>
<td>Decreased development of pre-neoplastic lesions with increased n-3 FA component</td>
</tr>
<tr>
<td>O’Connor et al. (1989)</td>
<td>Rats treated with aspirin to induce pre-neoplastic pancreatic lesions + different n-3:n-6 FA ratios</td>
<td>Decreased incidence of liver metastases in n-3 FA group. Decreased incidence of macroscopically visible pancreatic tumours in n-3 FA, although microscopic appearances are not different from other FA groups</td>
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<tr>
<td>Heukamp et al. (2006), Gregor et al. (2006)</td>
<td>Hamsters treated with BOP to induce PC + n-6 FA-rich diet followed by n-3 or n-3, -6 and -9 FA-rich diet</td>
<td>Incidence, frequency and proliferation index of pancreatic pre-cancer reduced with n-3 FA-rich diet. Decrease in cell line proliferation and induction of apoptosis with DHA</td>
</tr>
<tr>
<td>Strouch et al. (2009)</td>
<td>EL-Kras mice + n-3 FA-rich diet or standard diet PC cell lines + DHA</td>
<td>Decreased cell growth with n-3 FA. Decrease in growth in mouse model with n-3 FA-rich diet</td>
</tr>
<tr>
<td>Funahashi et al. (2008)</td>
<td>PC cell lines + n-3 FA or n-6 FA. Mice injected with PC cells + n-3 or n-6 FA-rich diet. Bovine endothelial cells treated with VEGF + n-3 or n-6 FA</td>
<td>Suppression of VEGF-induced proliferation with EPA</td>
</tr>
<tr>
<td>Yang et al. (1998)</td>
<td>Bovine endothelial cells treated with VEGF + n-3 or n-6 FA</td>
<td>Inhibition of VEGF-stimulated migration and tube formation. Reduction in MMP2 and MMP9</td>
</tr>
<tr>
<td>Tsuzuki et al. (2007)</td>
<td>Human umbilical vein cells treated with VEGF + EPA</td>
<td>Inhibition of VEGF-stimulated migration and tube formation and VEGF receptor 2 expression strongest with DPA compared with DHA or EPA</td>
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<tr>
<td>Tsuji et al. (2003)</td>
<td>Bovine endothelial cells treated with VEGF + EPA or DPA or DHA.</td>
<td>Inhibition of PDGF production with EPA</td>
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<td>Fox &amp; DiCorleto (1988)</td>
<td>Vascular endothelial cells + EPA</td>
<td>Inhibition of vascular smooth muscle proliferation through inhibition of PDGF signal transduction with EPA greater than DHA</td>
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<tr>
<td>Terano et al. (1996)</td>
<td>Vascular smooth muscle cells + EPA or DHA</td>
<td>NO production in response to lipopolysaccharide reduced by n-3 FA-rich diet</td>
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<td>Boutard et al. (1994)</td>
<td>Macrophages isolated from rats fed n-3 FA-rich or-deficient diets.</td>
<td>DHA inhibitory to NO production at all doses of IFN-γ or TNF-α</td>
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<tr>
<td>Jeyarajah et al. (1999)</td>
<td>Mouse macrophages (treated with IFN-γ or TNF-α) + DHA</td>
<td>Inhibition of NO production with n-3 FA in contrast to no inhibition with any other FA regimen</td>
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<tr>
<td>Ohata et al. (1997)</td>
<td>Mouse macrophage cell line treated with lipopolysaccharide + n-3, n-6, n-9 FA or stearic acid</td>
<td>Inhibition of growth and induction of apoptosis greatest with low-dose combination of DHA + celecoxib</td>
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<tr>
<td>Narayanan et al. (2005)</td>
<td>Prostate cancer cell lines + DHA + celecoxib (COX-2 inhibitor)</td>
<td>Inhibition of tumour incidence in multiplicity in n-3 FA-rich diet with low-dose celecoxib</td>
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<tr>
<td>Reddy et al. (2005)</td>
<td>Colon cancer rat model + celecoxib + n-3 FA-rich or-deficient diet</td>
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PC, pancreatic cancer; FA, fatty acids; GLA, γ-linolenic acid; ALA, α-linolenic acid; BOP, N-nitrosobis(2-oxopropyl)amine; VEGF, vascular endothelial growth factor; MMP, matrix metalloproteinase; DPA, docosapentaenoic acid; PDGF, platelet-derived growth factor; IFN, interferon; COX, cyclo-oxygenase.
They inhibit the growth of human pancreatic adenocarcinoma cell lines in a dose-dependent manner\(^\text{15}\). They also induce apoptosis of the same cells in a dose-dependent manner\(^\text{7,9–12}\). They have been shown to inhibit proliferation in gemcitabine-resistant cell lines irrespective of the level of gemcitabine resistance\(^\text{13}\). There are various mechanisms postulated for this action including the induction of apoptosis, cell cycle arrest, intracellular glutathione depletion, down-regulation of cyclin E and inhibition of NF-κB expression\(^\text{10,14}\).

In rat models given azaserine to induce neoplastic lesions, a diet with a high \(n\)-3:fat ratio of fatty acids decreased the development of pre-neoplastic atypical acinar cell nodules\(^\text{15}\). A different model using \(N\)-nitrosobis-2-oxpropylnime to induce ductal pancreatic adenocarcinoma in rats found that a group fed with a diet rich in \(n\)-3 fatty acids only had significantly lower incidence of macroscopic tumours and liver metastases compared with the groups fed on a diet rich in \(n\)-6 fatty acids alone, or \(n\)-3, -6 and -9 fatty acids together\(^\text{16,17}\). More recently, the incidence, frequency and proliferative index of pre-neoplastic pancreatic lesions in an experimental rat model has been shown to be reduced in the cohort fed on a high-\(n\)-3 fat diet\(^\text{18}\). \(n\)-6 Fatty acids have been shown to stimulate the development of pancreatic carcinoma in xenograft models through the increased production of cyclo-oxygenase-2-generated PGE\(_2\), whereas in the same model, \(n\)-3 fatty acids were shown to reduce the development of pancreatic carcinoma through the reversal of the PGE\(_2\)/PGE\(_3\) ratio\(^\text{19}\).

Rapidly growing tumours require new blood vessel formation or angiogenesis in order to initiate and sustain proliferation. Angiogenesis is dependent on many different growth factors, in particular vascular endothelial growth factor and platelet-derived growth factor. \(n\)-3 Fatty acids suppress vascular endothelial growth factor-stimulated cell proliferation, migration and tube formation during angiogenesis\(^\text{20–22}\). \(n\)-3 Fatty acids inhibit the production of platelet-derived growth factor-like protein from vascular endothelial cells and inhibit vascular smooth muscle proliferation by interfering with the platelet-derived growth factor signalling pathway\(^\text{23,24}\). In addition, angiogenesis is critically dependent upon the production of NO and the action of cyclo-oxygenase-2. \(n\)-3 Fatty acids inhibit NO production and NO synthase in vitro as well as in animal models\(^\text{25–27}\). Several recent studies have shown that \(n\)-3 fatty acids combined with cyclo-oxygenase-2 inhibitors inhibit growth in experimental cancer cell lines and xenograft models\(^\text{28,29}\).

Furthermore, \(n\)-3 fatty acids have been shown to potentiate the effects of gemcitabine chemotherapy on human cancer cell lines. The postulated mechanisms for this action include up-regulation of cytotoxic transporters and initiation of oxidative stress processes.

### Human studies into the effects on tumour-related cachexia and quality of life

It has been suggested for 20 years that \(n\)-3 fatty acids may be useful in the alleviation of tumour-related cachexia\(^\text{30}\). In particular, most studies have been performed on patients with pancreatic and upper gastrointestinal tract cancers, although there are some data showing a benefit in patients with other solid cancers\(^\text{31}\). Barber \textit{et al.}\(^\text{32–34}\) showed that patients with pancreatic cancer given approximately 2 g of EPA and 1 g of DHA for 7 weeks showed significant weight gain and improvement in functional status and appetite, in both one single- and two double-arm non-randomised studies comprising seventy-two patients and twelve controls. It was also shown that high doses (up to 18 g) of EPA were well tolerated but with greater side effects such as pain, steatorrhoea and...
nausea\(^{(35,36)}\). Burns \textit{et al.}\(^{(56)}\) went on to show 66% weight stabilisation and 17% weight gain in the twenty-two patients they enrolled in a single-arm study, with the best QOL scores in the patients with weight gain. Wigmore \textit{et al.}\(^{(37)}\) showed significant weight gain, with a mean of 0·3 kg/month in pancreatic cancer patients given fish oil for 3 months, as well as stabilisation of resting energy expenditure by indirect calorimetry. They went on to examine an escalating dose of EPA from 1 g/d for 4 weeks to 6 g/d for 12 weeks. This study showed a weight gain of 0·5 kg at 1 month, which remained stable at 12 weeks\(^{(38)}\). The best-quality and largest study in pancreatic cancer patients to date is from Fearon \textit{et al.}\(^{(39)}\) who randomised 200 patients to receive 2·2 g EPA/d or placebo. They noted weight and lean tissue gain in the EPA group as well as improved QOL scores. Bruestra \textit{et al.}\(^{(40)}\), however, noted no difference in weight, functional status or well-being in their randomised controlled trial comprising sixty patients given either DHA + EPA or olive oil, although it should be noted that this group had tumours of diverse anatomical origin. Kenler \textit{et al.}\(^{(41)}\) studied thirty-five patients with surgically operated upper gastrointestinal malignancies and noted a significant reduction in gastrointestinal complications of distension, diarrhoea and nausea, with a significant decrease in the need for total parenteral nutrition and improvement in liver and renal function in the EPA/DHA group. Moses \textit{et al.}\(^{(42)}\) found a significant increase in total resting energy expenditure and physical activity level in the patients to whom they gave EPA for 8 weeks. In summary, there does seem to be at least some evidence to show a beneficial relationship of fish oils rich in \(n\)-3 fatty acids in the alleviation of tumour-related cachexia and improving QOL scores. There is limited evidence on the optimal dose: these studies all used oral supplementation, although most showing benefit used a dose >1·5 g/d, with some showing improved results in the 1·5–4·0 g/d range\(^{(43)}\). In addition, many of these studies reported problems with patient compliance in taking the oral \(n\)-3 fatty acid preparations, mainly due to the large number of tablets or volume of liquid that was required to achieve the desired dose.

**Clinical applications of parenteral fish oils rich in \(n\)-3 fatty acids**

Many studies have reported beneficial immunomodulatory and nutritional effects of \(n\)-3 fatty acid containing lipid emulsions as part of total parenteral nutrition\(^{(44,45)}\). So far, few have examined the use of \(n\)-3 fatty acid emulsions independently in the treatment of inflammatory conditions, and there are no published case series or controlled trials of intravenous \(n\)-3 fatty acid preparations in the adjuvant treatment of cancers. However, animal models as discussed previously using \(n\)-3 fatty acid preparations do support the potential utility of \(n\)-3 fatty acid emulsions in the adjuvant treatment of human pancreatic adenocarcinoma. Notwithstanding the potential direct tumour effect and potential response for patients undergoing chemotherapy for unresectable pancreatic adenocarcinoma, there is a reasonable body of evidence that QOL scores and tumour cachexia may be improved\(^{(30–39)}\).

High-strength oral preparations are available, as mentioned previously, with EPA purity of up to 95% containing up to 18 g of EPA in 100 ml of emulsion\(^{(35)}\). However, data concerning the oral bioavailability of EPA and DHA are limited, and there are no published data comparing oral and intravenous bioavailability\(^{(46)}\). Intravenous preparations containing 10 g of \(n\)-3 TAG per 500 ml are commercially available.

The safety of high-dose \(n\)-3 fatty acid parenteral emulsions is well established when it has been used as a component of total parenteral nutrition, but further studies would be required to establish its tolerability and efficacy as a combination therapy in conjunction with gemcitabine chemotherapy for the treatment of APC.

**Conclusions**

The effective palliative treatment of patients with APC has undergone very little advancement in terms of improving overall survival, since gemcitabine chemotherapy was first introduced 16 years ago\(^{(47)}\). Novel agents that can prolong survival, improve QOL and alleviate cachexia in patients with APC are currently unavailable. Putative adjuvant therapies including parenteral \(n\)-3 fatty acid emulsions have the potential to address all of these outcome targets and have the additional benefit of proven safety and tolerability albeit in a different study population. The marginal benefits on tumour cachexia and QOL shown in trials using oral \(n\)-3 fatty acid supplementation may warrant further investigation with parenteral preparations as compliance and maintenance of optimal dosing should be easier to achieve. Clinical trials to investigate \(n\)-3 fatty acid emulsions in combination with gemcitabine in patients with APC are clearly warranted. Even if there is no demonstrated anti-neoplastic activity, an improvement in cachexia and QOL could result in \(n\)-3 fatty acid emulsions becoming part of standard care in this challenging patient group.

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**References**


