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Cod liver oil: feed oil influences on fatty acid composition

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Abstract The influence of feed oils on fatty acid compositions of cod liver oils was examined to investigate how fatty acid profiles are modified, and to provide estimates of feed oil compositions needed to give liver oils meeting production guidelines [3–11% 18:2*n*−6, 7–16% 20:5*n*−3 (EPA) and 6–18% 22:6*n*−3 (DHA)]. Attention was directed to examination of cod liver oil contents of *n*−6 and *n*−3 fatty acids, the essential fatty acids. Data, mostly taken from published work, were subjected to regression analysis to investigate the relationships between the percentages of fatty acids (18:2*n*−6, total *n*−6 fatty acids, 18:3*n*−3, 20:5*n*−3, 22:6*n*−3 and total *n*−3 fatty acids) in feed oils and their percentages in liver oils.

There were highly significant relationships between feed oil and liver oil percentages for all fatty acids examined:

Liver oil 18:2*n*−6 (%) = 0.787 Feed oil 18:2*n*−6 (%) + 1.329; ($n = 21$; $R^2 = 0.957$)
Liver oil total *n*−6 Fatty acids (%) = 0.831 Feed oil total *n*−6 Fatty acids (%) + 0.536; ($n = 21$; $R^2 = 0.957$)
Liver oil 18:3*n*−3 (%) = 0.814 Feed oil 18:3*n*−3 (%) + 0.022; ($n = 21$; $R^2 = 0.985$)
Liver oil 20:5*n*−3 (%) = 0.762 Feed oil 20:5*n*−3 (%) + 1.163; ($n = 21$; $R^2 = 0.875$)
Liver oil 22:6*n*−3 (%) = 0.785 Feed oil 22:6*n*−3 (%) + 1.393; ($n = 21$; $R^2 = 0.831$)
Liver oil total *n*−3 Fatty acids (%) = 0.770 Feed oil total *n*−3 Fatty acids (%) + 2.558; ($n = 21$; $R^2 = 0.851$)

Feed oil percentages of 18:2*n*−6, 20:5*n*−3 (EPA) and 22:6*n*−3 (DHA) required to produce liver oils that comply with guidelines were estimated to be 2.5–12.5% for 18:2*n*−6, 8–19.5% for 20:5*n*−3 and 6–21% for 22:6*n*−3. Given the fatty acid compositions of commercial feed oils it is unrealistic to expect that liver oils with highly unsaturated *n*−3 fatty acids percentages at the high end of the recommended range (15–18% for both 20:5*n*−3 and 22:6:*n*−6) can be produced from farmed cod, but it should be possible to

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obtain liver oils that fulfil fatty acid composition criteria without the need to manufacture feeds that have fatty acid compositions that deviate markedly from those in current use. As an alternative to using feeds with constant fatty acid compositions throughout production, finisher feeds could be used to manipulate fatty acid compositions of liver oils, but the economics of using this feeding strategy needs to be examined before commercial implementation can be recommended.

Keywords Human nutrition · Dietary lipids · $n-3$ HUFAs · $n-6$ PUFAs · Marine fish oils · Plant oils · *Gadus morhua*

Introduction

Highly unsaturated $n-3$ fatty acids ($n-3$ HUFAs), particularly 20:5$n-3$ (EPA) and 22:6$n-3$ (DHA), are important for human health and early development, and dieticians are advising increased consumption of foods that contain these fatty acids (Connor 2000; Williams 2000; McCowen and Bistrian 2005; Ruxton et al. 2005, 2007; Lunn and Theobald 2006). It is recommended that the dietary ratio of $n-6$ to $n-3$ fatty acids be maintained below 5:1, but the diets of most western Europeans and North Americans are characterised by $n-6$ to $n-3$ fatty acid ratios (7–20) that deviate markedly from recommendations (Bourre 2005; Lunn and Theobald 2006; Lacroix and De Meester 2007). Ways in which the balance could be redressed would be by increasing consumption of seafood and/or taking $n-3$ HUFA-rich dietary supplements. The fillets of oily fish contain 5–20% lipid, depending upon species and season, and oily marine fish are the main source of $n-3$ HUFAs in the human diet (Jobling 2001, 2004b; Bourre 2005; Ruxton et al. 2005, 2007; Lunn and Theobald 2006). As an alternative to eating oily marine fish to obtain $n-3$ fatty acids, marine fish oils may be taken as a dietary supplement; $n-3$ HUFAs may make up 20–30% of the fatty acids in marine fish oils, and a dose of 5 g oil (ca. 5 ml) would provide 1–1.5 g $n-3$ HUFAs to a human consumer (Bourre 2005; Ruxton et al. 2005; Lunn and Theobald 2006). Cod liver oil has a long tradition of use as a dietary supplement, and is widely consumed as a source of $n-3$ HUFAs and lipid-soluble vitamins (vitamins A and D).

Cod farming industries are developing on the Atlantic seaboards of northern Europe and North America, and it is currently the lean, white-fleshed fillet that is the main saleable product. It is, however, not unusual for farmed cod to develop large, oily livers (Lie et al. 1986; dos Santos et al. 1993; Jobling 2001, 2004b; Bell et al. 2006; Karalazos et al. 2007; Standal et al. 2008), making the livers of farmed cod a potentially valuable commodity for the production of cod liver oil (Jobling 2004b; Standal et al. 2008). For this to be a viable proposition there would need to be a large and regular supply of livers from farmed cod, and the extracted oils would need to contain high concentrations of $n-3$ HUFAs and low concentrations of contaminants (Jobling 2004b; Standal et al. 2008); guidelines for fatty acid compositions of liver oils from farmed cod have been proposed (Standal et al. 2008).

There is increasing use of plant oils to partially replace marine fish oils in the feeds given to farmed fish. This is becoming common because of a combination of a shortfall in supply and increasing prices of feed-quality fish oils. The replacement of fish oils by plant oils may create some problems for farmed fish production because marine fish oils are good sources of $n-3$ HUFAs whereas plant oils are not. Many plant oils contain quite high percentages of 18C $n-3$ fatty acids but they are devoid of $n-3$ HUFAs. As such, fish species that have limited ability to convert 18C $n-3$ fatty acids to $n-3$ HUFAs will not deposit much $n-3$ HUFA in their tissues (Sargent et al. 1989, 2002; Higgs and Dong 2000; Jobling 2001, 2004b).

With this background the present work was carried out with the aim of investigating the influence of feed oil blends on the fatty acid compositions of liver oils of farmed cod, and to provide a preliminary estimate of the compositions of feed oils that would be needed to produce liver oils that comply with fatty acid composition guidelines (Standal et al. 2008).

Materials and methods

Data used in the analyses were compiled from published work, and also included some unpublished information from our studies. The unpublished data relate to analyses of total $n-6$ and $n-3$ fatty acids undertaken in connection with the fatty acid determinations presented in Jobling et al. (2008). The other information was taken from Lie et al. (1986), dos Santos et al. (1993), Bell et al. (2006), Karalazos et al. (2007), Jobling et al. (2008) and Zhong et al. (2008). Several of the published studies included treatments in which there was partial replacement of fish oil with plant oils or plant oil blends, namely peanut (Lie et al. 1986), echium (Bell et al. 2006), soya (Karalazos et al. 2007) or rapeseed and linseed oils (Jobling et al. 2008).

In performing analyses attention was directed towards examination of the influences of feed oil contents of $n-6$ and $n-3$ fatty acids (the essential fatty acids) on the fatty acid compositions of the liver oils. The relationships between the percentages of fatty acids (18:2$n-6$, total $n-6$, 18:3$n-3$, 20:5$n-3$, 22:6$n-3$ and total $n-3$) in feed oils and the resulting liver oils were examined using least-squares regression analysis. The regression lines generated for 18:2$n-6$, 20:5$n-3$ (EPA) and 22:6$n-3$ (DHA) were then used to estimate the percentages of fatty acids in feed oil blends that would be needed to produce liver oils that complied with guideline values for cod liver oils destined for human consumption (Standal et al. 2008).

Results

There were highly significant relationships between feed oil and liver oil percentages for all fatty acids examined (Figs. 1–4). The $n-6$ fatty acids are characteristic of plant oils, and the highest percentages of 18:2$n-6$ and total $n-6$ fatty acids were recorded in the liver oils of cod that had been given feeds containing peanut (Lie et al. 1986), echium (Bell et al. 2006), soya (Karalazos et al. 2007) or rapeseed (Jobling et al. 2008) oil as a substantial proportion of the dietary lipid source (Fig. 1). Percentages of total $n-3$ fatty acids increased with increasing dietary supply (Fig. 2), irrespective of whether they were provided in the form of 18C $n-3$ fatty acids or $n-3$ HUFAs (Figs. 2–4). Some plant oils, such as linseed and echium oils, contain a high percentage of 18:3$n-3$, and the highest percentages of this $n-3$ fatty acid were recorded in the liver oils of cod given feeds in which echium oil (Bell et al. 2006) or linseed oil (Jobling et al. 2008) was used as a source of dietary lipid. The $n-3$ HUFAs are characteristic of marine food chains, and the highest percentages of 20:5$n-3$ (EPA) and 22:6$n-3$ (DHA) were recorded in the liver oils of cod given feeds in which oils of marine origin were used as the main source of dietary lipid (Figs. 3 and 4).

The guidelines developed for the fatty acid compositions of liver oils from farmed cod state that 18:2$n-6$ may be within the range 3–11%, 20:5$n-3$ should make up 7–16% and 22:6$n-3$ should make up 6–18% of the fatty acids present in the oil (Standal et al. 2008).

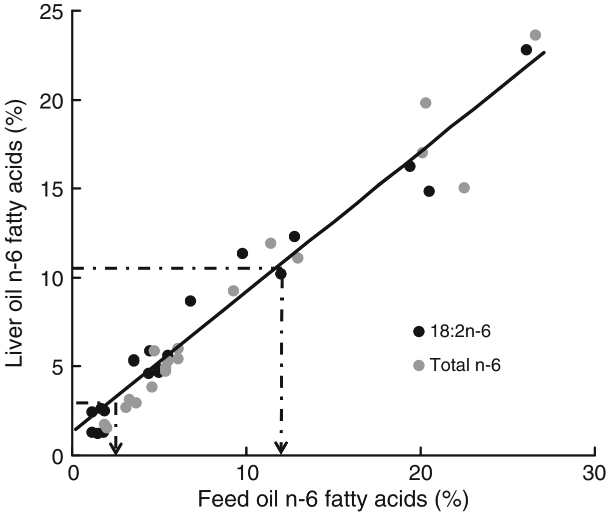

Fig. 1 Influence of $n-6$ fatty acids in feed oils on $n-6$ fatty acids in the liver oils of farmed cod. Regression equations for the relationships are: Liver oil total $n-6$ FAs (%) = 0.831 Feed oil total $n-6$ FAs (%) + 0.536 ($n = 21$; $R^2 = 0.957$); Liver oil 18:2$n-6$ (%) = 0.787 Feed oil 18:2$n-6$ (%) + 1.329 ($n = 21$; $R^2 = 0.957$). The *solid line* shows the relationship between feed oil 18:2$n-6$ and liver oil 18:2$n-6$. The *horizontal dashed lines* indicate the guideline range for percentage 18:2$n-6$ in the liver oils of farmed cod (Standal et al. 2008) and the *vertical arrows* represent the estimates of the percentages of the fatty acid needed to be included in feed oil blends to produce cod liver oils that comply with the guidelines

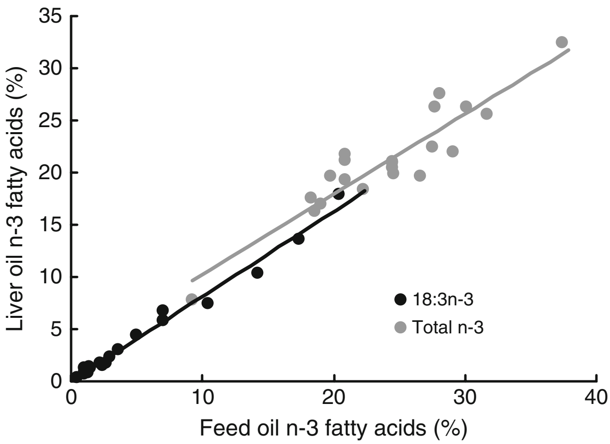

Fig. 2 Influence of $n-3$ fatty acids in feed oils on $n-3$ fatty acids in the liver oils of farmed cod. Regression equations for the relationships are: Liver oil total $n-3$ FAs (%) = 0.770 Feed oil total $n-3$ FAs (%) + 2.558 ($n = 21$; $R^2 = 0.851$); Liver oil 18:3$n-3$ (%) = 0.814 Feed oil 18:3$n-3$ (%) + 0.022 ($n = 21$; $R^2 = 0.985$). The *solid black line* shows the relationship between feed oil 18:3$n-3$ and liver oil 18:3$n-3$, and the *grey line* shows the relationship for total $n-3$ fatty acids

The percentages of 18:2$n-6$, 20:5$n-3$ (EPA) and 22:6$n-3$ (DHA) required to be present in feed oil blends to produce cod liver oils complying with guidelines were estimated to be 2.5–12.5% for 18:2$n-6$ (Fig. 1), 8–19.5% for 20:5$n-3$ (Fig. 3) and 6–21% for 22:6$n-3$ (Fig. 4).

Closer examination revealed that when the percentages of $n-3$ HUFAs in liver oils met guideline criteria they were almost invariably at the low to mid end of the range suggested by Standal et al. (2008) (Figs. 3 and 4). These results were obtained despite the fact that all of the studies in the analysis included treatments in which marine fish oils, relatively rich in $n-3$ HUFAs, were used as the main source of dietary lipids.

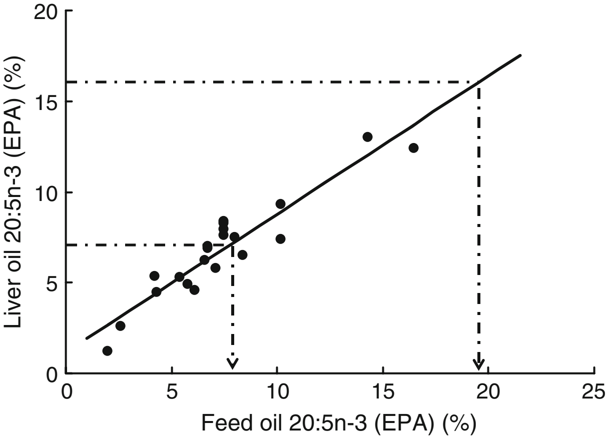

Fig. 3 Relationship between 20:5n−3 in feed oils and the percentage of this fatty acid in the liver oils of farmed cod. The regression equation for the relationship is: Liver oil 20:5n−3 (%) = 0.762 Feed oil 20:5n−3 (%) + 1.163 (n = 21; R^2 = 0.875). The *horizontal dashed lines* indicate the guideline range for percentage 20:5n−3 in the liver oils of farmed cod (Standal et al. 2008) and the *vertical arrows* represent the estimates of the percentages of the fatty acid needed to be included in feed oil blends to produce cod liver oils that comply with the guidelines

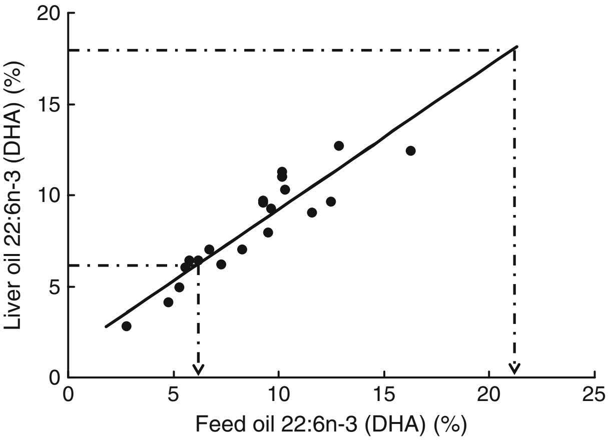

Fig. 4 Relationship between 22:6n−3 in feed oils and the percentage of this fatty acid in the liver oils of farmed cod. The regression equation for the relationship is: Liver oil 22:6n−3 (%) = 0.785 Feed oil 22:6n−3 (%) + 1.393 (n = 21; R^2 = 0.831). The *horizontal dashed lines* indicate the guideline range for percentage 22:6n−3 in the liver oils of farmed cod (Standal et al. 2008) and the *vertical arrows* represent the estimates of the percentages of the fatty acid needed to be included in feed oil blends to produce cod liver oils that comply with the guidelines

Discussion

The types of oil used as lipid sources in cod feeds have a marked influence on the fatty acid compositions of cod liver oils (Figs. 1–4). The two fatty acids 18:2n−6 and 18:3n−3 are precursors for synthesis of n−6 and n−3 HUFAs, respectively (Sargent et al. 1989, 2002; Higgs and Dong 2000). Deposition of 18:2n−6 and 18:3n−3 in the liver oils was highly correlated with the percentages present in feed oils (Figs. 1 and 2), so it appears that these two fatty acids, rather than their HUFA derivatives, were incorporated directly into the liver oils. As such, the percentages of total $n-3$ fatty acids in the liver oils were increased by using feed oils that were rich in 18C $n-3$ fatty acids (Fig. 2); some plant oils, such as linseed oil and borage and echium oils, are good sources of these fatty acids. On the other hand, it seems that only a small proportion of the 18C $n-3$ fatty acids was converted to $n-3$ HUFAs by the cod, leading to deposition of 18:3$n-3$ and 18:4$n-3$, rather than 20:5$n-3$ (EPA) and 22:6$n-3$ (DHA), in the liver oils. The suggestion is, therefore, that cod have limited ability to use 18:2$n-6$ and 18:3$n-3$ for production of $n-6$ and $n-3$ HUFAs, and the general consensus is that carnivorous marine fish have limited capacity to produce HUFAs via chain elongation and desaturation of the 18C $n-3$ and $n-6$ precursors (Sargent et al. 1989, 2002; Higgs and Dong 2000).

Although 18:3$n-3$ is usually assigned essential fatty acid status because it can be used as a precursor for the formation of $n-3$ HUFAs the bioconversion is relatively inefficient in humans (Connor 2000; Williams 2000; McCowen and Bistrian 2005; Ruxton et al. 2005, 2007; Lunn and Theobald 2006). The synthesis of $n-3$ HUFAs from 18:3$n-3$ is especially inefficient when the diet contains high concentrations of 18:2$n-6$, because the two 18C fatty acids compete for conversion via a common series of elongase and desaturase enzymes (Sargent et al. 1989, 2002; Connor 2000; Lunn and Theobald 2006). Using this information about fatty acid bioconversion, it is open to question whether or not it would be advisable to boost the $n-3$ fatty acid contents of the liver oils of farmed cod by providing the fish with feeds that contain high proportions of linseed, or other plant oils that are rich in 18C $n-3$ fatty acids. On the other hand, feeds containing linseed or linseed oil are being used to manipulate the fatty acid compositions of food products, such as eggs, milk and meat, derived from terrestrial livestock (Bourre 2005; Lunn and Theobald 2006; Lacroix and De Meester 2007). These are marketed as $n-3$ (or omega-3) enriched products, but they contain mostly 18C $n-3$ fatty acids rather than $n-3$ HUFAs. Although there is potential for using a similar strategy for the production of cod liver oils this would probably be inadvisable.

Liver oil percentages of $n-3$ HUFAs are under the influence of the amounts of these fatty acids supplied via the feed (Figs. 3 and 4), but when the cod liver oils considered in the present study met the criteria outlined by Standal et al. (2008), the percentages of $n-3$ HUFAs were usually at the low end of the range (Figs. 3, 4). In practice, there are no commercial feed oils that contain the percentages of $n-3$ HUFAs (over 15% for both 20:5$n-3$ and 22:6$n-3$) that would be required to produce cod liver oils containing the highest percentages suggested by Standal et al. (2008), and it would not be economic to include $n-3$ HUFA concentrates in feeds for farmed cod. Thus, it was found that none of the liver oils contained percentages of $n-3$ HUFAs at the high end of the range proposed by Standal et al. (2008), and given the fatty acid compositions of commercial feed oils it is unrealistic to expect that liver oils with such high levels of $n-3$ HUFAs can be produced from farmed cod. Nevertheless, it is possible to obtain liver oils that fulfil the Standal et al. (2008) fatty acid composition criteria without the need to manufacture cod feeds that have fatty acid compositions that deviate markedly from those currently in use.

A major point of note is that the fatty acid compositions of cod liver oils appear to be extremely labile; fatty acid compositions of the liver oils are readily modified following changes in the type of oil used in feed manufacture. Thus, as an alternative to using feeds of constant fatty acid composition throughout the production cycle, it may also be possible to use finisher feeds to manipulate the fatty acid compositions of cod liver oils. Hitherto, the finisher feed strategy has largely been used to change the fatty acid profiles of the fillet lipids of oily fish such as farmed Atlantic salmon, *Salmo salar*, in order to boost the percentages of $n-3$ HUFAs present in the edible portion of the fish (Bell et al. 2003a, b; Jobling 2004a). This strategy may also have more widespread application because we have demonstrated the feasibility of using this strategy to manipulate the fatty acid composition of cod liver oil in desired directions (Jobling et al. 2008). The economics of using such a strategy must, however, be examined in detail before implementation can be recommended on a commercial scale.

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