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Factors influencing fatty acids in meat and the role of antioxidants in improving meat quality

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Meat has been identified, often wrongly, as a food having a high fat content and an undesirable balance of fatty acids. In fact lean meat is very low in fat (20–50 g/kg), pork and poultry have a favourable balance between polyunsaturated and saturated fatty acids (P:S) and grazing ruminants produce muscle with a desirable *n*-6:*n*-3 polyunsaturated fatty acid ratio. In all species, meat fatty acid composition can be changed via the diet, more easily in single-stomached pigs and poultry where the linoleic, α-linolenic and long-chain polyunsaturated fatty acid content responds quickly to raised dietary concentrations. Recent work in pigs has attempted to manipulate the *n*-6:*n*-3 ratio by feeding higher levels of α-linolenic acid (e.g. in rapeseed) or its products eicosapentaenoic acid (20:5) and docosahexaenoic acid (22:6) present in fish oils. In ruminants the challenge is to increase the P:S ratio whilst retaining values for *n*-6:*n*-3 found in cattle and sheep fed on forage diets. The saturating effect of the rumen can be overcome by feeding polyunsaturated fatty acids which are protected either chemically, by processing, or naturally e.g. within the seed coat. Some protection occurs when grain-based or grass-based diets are fed normally, leading to relatively more *n*-6 or *n*-3 fatty acids respectively. These produce different flavours in cooked meat due to the different oxidative changes occurring during storage and cooking. In pigs and poultry, high *n*-3 fatty acid concentrations in meat are associated with fishy flavours whose development can be prevented with high dietary (supranutritional) levels of the antioxidant vitamin E. In ruminants, supranutritional vitamin E delays the oxidative change of oxymyoglobin to brown metmyoglobin and may also influence the characteristic flavours of beef and lamb.

Meat: Fatty acids: Antioxidants

In recent years awareness of the importance of diet in human health has increased. Many authorities have recommended that the contributions of fat and especially saturated fatty acids to dietary energy intake should be reduced. In the UK recent recommendations are 35 % of energy for fat and 10 % of energy for saturated fatty acids (Department of Health, 1994). Within these general guidelines more particular advice is to reduce the intake of short- and medium-chain saturated fatty acids and the intake of *n*-6 polyunsaturates relative to *n*-3 (Gibney, 1993). Although it is the dietary balance of fatty acids in the total diet which is physiologically important, attempts have been made with many individual foods to change them in line with the new dietary guidelines in order to make them more attractive to consumers. The present paper considers the options for meat, a food which has been criticized on the grounds of its fat and fatty acid content.

FAT AND FATTY ACID COMPOSITION OF RED MEATS

A recent study by Bristol University investigated the fat content and composition of steaks or chops from equivalent parts of the carcass (the loin) in beef, lamb and pork. The results (Table 1) showed that the lean meat (muscle) is low in fat in all three species (20–50 g/kg) but particularly pork. In the steaks as purchased, dissectible fat contents were 156, 302 and

Table 1. *Fatty acid content of loin muscle (mg/g) in steaks or chops purchased from four supermarkets* (Adapted from Enser *et al.* 1996)

Fatty acid	Beef	Lamb	Pork
12:0 (lauric)	2·9	13·8	2·6
14:0 (myristic)	103	155	30
16:0 (palmitic)	962	1101	526
18:0 (stearic)	507	898	278
18:1 *trans*	104	231	–
18:1 (oleic)	1395	1625	759
18:2*n*-6 (linoleic)	89	125	302
18:3*n*-3 (α-linolenic)	26	66	21
20:3*n*-6	7	2	7
20:4*n*-6 (arachidonic)	22	29	46
20:5*n*-3 (eicosapentaenoic)	10	21	6
22:5*n*-3 (docosapentaenoic)	16	24	13
22:6*n*-3 (docosahexaenoic)	2	7	8
Total	3835	4934	2255
P:S	0·11	0·15	0·58
n-6:*n*-3	2·11	1·32	7·22

P:S, polyunsaturated:saturated fatty acid ratio, i.e. $\frac{18{:}2n\text{-}6 + 18{:}3n\text{-}3}{12{:}0 + 14{:}0 + 16{:}0}$.

211 g/kg in beef, lamb and pork respectively. Many people remove visible fat before consuming meat and fat is also lost during cooking.

The fatty acid composition of total lipid extracted from the lean showed clear differences between the species (Table 1). Beef and lamb had a low polyunsaturated:saturated fatty acids (P:S) ratio compared with pork due mainly to the high linoleic acid content of pork. However this also caused beef and lamb to have a more favourable *n*-6:*n*-3 fatty acids ratio. Recommended values are 0·45 for P:S and below 4·0 for *n*-6:*n*-3.

On the basis of results like these, researchers have particularly focused on ways to increase the P:S ratio of ruminant meats and correct the imbalance between *n*-6 and *n*-3 fatty acids in pork and also in poultry.

ASSOCIATIONS BETWEEN FAT CONTENT AND FATTY ACID COMPOSITION

In pigs, a strong inverse correlation between the amount of fat and the concentration of the main polyunsaturated fatty acid linoleic acid has been observed in several studies. The results in Table 2 are taken from a study of 300 pigs in which lean, intermediate and fat pigs were identified in individual producer groups. These values are therefore independent of feeding regimen which may differ from farm to farm. There were strong correlations between fatty acid concentrations and the firmness of fat tissue; high linoleic acid and low stearic acid concentrations indicated softer fat in leaner carcasses. This tendency towards more unsaturated fat in leaner meat holds however leanness is achieved, for example it is true in entire males compared with castrates and in pigs fed restrictedly compared with those fed *ad libitum* (Table 3). In the study of Wood *et al.* (1996) (Table 3), the inverse correlation between unsaturated fatty acid concentration and lipid content was absent for the major *n*-3 fatty acid α-linolenic which suggests different control factors for the concentrations of linoleic and α-linolenic acids, both of which are entirely derived from the diet and compete for inclusion into tissue lipids.

Table 2. *Fatty acid composition (g/100 g total fatty acids) in total lipids of pig backfat according to carcass fat content* (Adapted from Wood *et al.* 1989)

	P_2 fat thickness (mm)*		
	8	12	16
Lipid (g/kg wet wt)	692	770	816
Fatty acids			
18:0 (stearic)	13·1	13·8	13·9
18:1 (oleic)	40·3	41·8	43·1
18:2 (linoleic)	14·9	12·4	10·6
18:3 (α-linolenic)	1·1	0·9	0·8

* Thickness of subcutaneous fat and skin above *m. longissimus* 65 mm from the dorsal midline at the level of the last thoracic vertebra.

Table 3. *Fatty acid composition (g/100 g total fatty acids) of marbling fat (total lipid in* m. longissimus*) in Duroc and Large White pigs fed at a high or low level* (Adapted from Wood *et al.* 1996)

	Breed		Feed level	
	Large White	Duroc	High	Low
P_2 fat thickness (mm)‡	8·4	11·2***	10·1	9·4†
Marbling fat (g/kg)	5	14**	11	8†††
18:0 (stearic)	11·5	12·0	11·9	11·6
18:2*n*-6 (linoleic)	22·4	18·2***	19·2	21·5†††
18:3*n*-3 (α-linolenic)	2·0	2·5	2·1	2·4
20:4*n*-6 (arachidonic)	4·2	2·2***	3·0	3·4†

Mean values were significantly different from those for Large Whites: ** $P < 0{\cdot}01$, *** $P < 0{\cdot}001$.
Mean values were significantly different from those for the high feed level: † $P < 0{\cdot}05$, ††† $P < 0{\cdot}001$.
‡ Thickness of subcutaneous fat and skin above *m. longissimus* 65 mm from the dorsal midline at the level of the last thoracic vertebra.

In cattle and sheep the concentrations of polyunsaturated fatty acids in total lipid are low because of hydrogenation in the rumen. Oleic acid (18:1) increases with fat content (as it tends to do in pigs, see Table 2) but stearic acid falls, leading to a general increase in unsaturation and softness as fatness increases (Leat, 1975), unlike the situation in pigs.

EFFECTS OF DIET ON FATTY ACID COMPOSITION AND MEAT QUALITY

Single-stomached animals

In pigs and poultry, dietary fatty acids are absorbed unchanged from the intestine and incorporated into tissue lipids. The polyunsaturated fatty acids linoleic and α-linolenic cannot be synthesized and tissue concentrations respond rapidly to dietary changes. Saturated and monounsaturated fatty acids on the other hand are synthesized and their concentrations are less readily influenced by diet.

Early work in the USA by Ellis & Isbell (1926) showed that linoleic acid could be readily incorporated into fat tissues but at high levels presented 'soft fat' problems when the carcasses were processed. A review by Wood (1984) following UK studies into the causes of soft fat concluded that the critical reduction in lipid melting point occurred above 15 g linoleic acid/100 g total fatty acids of backfat when sufficient triacylglycerols contained both linoleic and oleic acid. This occurred when typical pig diets contained more than 16 g linoleic acid/kg and this concentration has since been used as a threshold for formulating pig diets in the UK.

The evidence that monounsaturated fatty acids do not raise blood cholesterol levels has led some workers to explore the feeding of diets rich in oleic acid to pigs. In one study, very high levels of high-oleic sunflowerseed oil increased the concentration of oleic acid in muscle lipid from 42 to 53 g/100 g (Rhee *et al.* 1990) and significantly increased taste panel scores for tenderness, juiciness and flavour. The effect on flavour is presumably due to changes in the concentrations of flavour precursors developed during cooking.

However, in a study by Shackelford *et al.* (1990) high levels of dietary oleic acid from sunflowerseed oil did not improve eating quality scores even though the concentration in muscle lipid was raised to 52 g/100 g. In this work, high levels of dietary low-erucic-acid rapeseed oil increased the muscle lipid concentration of α-linolenic acid to 3 g/100 g (Table 4) which led to an increase in the percentage of panellists detecting off-flavours in cured cooked ham served cold. A higher proportion of panellists (65 %) detected off-flavours in bacon and this was directly due to increased concentrations of linolenic acid derivatives formed during processing, i.e. 2-pentenal and 2,4-heptadienal. A similar effect of low-erucic-acid rapeseed oil on off-flavour development was found by Meyer *et al.* (1992) when the subcutaneous lipid concentration of α-linolenic acid was raised from 1 (control) to 5 g/100 g. The diet, fed between 30 and 102 kg live weight, contained 120 g oil/kg of which 11 g/100 g was α-linolenic acid. In this study, raising muscle lipid oleic acid concentration through feeding high-oleic-acid peanuts did not affect taste-panel scores.

Greater availability of rape products (another source of oleic acid) in Europe has led to studies of its utilization in pig diets. In one of these, full-fat rapeseed (FFR) was included at three levels during the growing and finishing stages of growth (Table 5). At the highest level (300 g/kg), raised concentrations of all the C18 unsaturated fatty acids occurred but particularly α-linolenic acid leading to a beneficial reduction in the *n*-6 : *n*-3 ratio. However, backfat was undesirably soft as shown by the lower penetrometer reading. These effects were partly reversed by withdrawing FFR at 70 kg live weight.

A potential benefit of feeding diets rich in α-linolenic acid is that increased deposition could lead to increased synthesis of the longer-chain polyunsaturated fatty acids, 20:5 (eicosapentaenoic acid, EPA) and 22:6 (docosahexaenoic acid, DHA) which are the *n*-3

Table 4. *Fatty acid composition (g/100 g total fatty acids) of* m. longissimus *and taste panel scores for ham produced using different diets* (Data from Shackelford *et al.* 1990)

Fatty acid	Dietary oil source* Control	Safflowerseed	Sunflowerseed	Low-erucic-acid rapeseed
18:1 (oleic)	47·4	48·8	51·7	45·9
18:2*n*-6 (linoleic)	6·7	10·4	8·4	12·3
18:3*n*-3 (α-linolenic)	1·5	1·4	1·5	3·0
Flavour†	5·5	5·7	5·2	5·0
Off-flavours†	2·5	7·9	13·9	25·2

* Oils were added to the basal diet (100 g/kg) of pigs between 20 and 100 kg live weight.
† Scores from a scale of 1–8 (unflavourful–flavourful).
‡ Percentage of panellists detecting off-flavours.

Table 5. *Fatty acid composition (g/100 g total fatty acids) and firmness of backfat in pigs fed with 0 or up to 300 g full-fat rapeseed (FFR)/kg diet between 25 and 95 kg live weight* (Data from Gill *et al.* 1995)

	FFR (g/kg diet)			
Fatty acid	0	150	300	300*
18:0 (stearic)	11·3	8·9	6·6	8·0
18:1 (oleic)	39·3	42·4	47·1	45·0
18:2*n*-6 (linoleic)	16·7	17·9	20·0	19·2
18:3*n*-3 (α-linolenic)	2·2	4·0	5·3	4·4
Penetrometer†	582	551	428	508

* Pigs transferred to 0 FFR diet at 70 kg live weight.
† Firmness units (0–1000).

fatty acids involved in decreasing the thrombotic tendency of blood. In a study by Romans *et al.* (1995*a*), increasing the dietary concentration of ground flaxseed from 0 to 150 g/kg in diets fed for 25 d increased the tissue concentration of α-linolenic acid in backfat and muscle (Table 6). However, although the concentration of EPA was increased in backfat there was no effect in muscle and DHA concentrations were unaffected in both tissues. In a follow-on study (Romans *et al.* 1995*b*) the effects of dietary α-linolenic acid on tissue levels were shown to occur very rapidly, within 7 d. In both studies the 150 g flaxseed/kg diet produced bacon which elicited a high proportion of negative comments on flavour grounds (e.g. 'fishy').

A more effective way to increase tissue concentrations of EPA and DHA is to supplement the diet with fish oils which are good sources of these fatty acids. In a study by Irie & Sakimoto (1992) a basal diet was supplemented with 20, 40 or 60 g refined sardine oil/kg and after 4 weeks on the 60 g/kg diet, EPA and DHA concentrations in backfat, and particularly perirenal fat, were much increased (Table 7). As EPA and DHA concentrations increased, those of oleic and linoleic acids decreased, causing no change in the melting point of extracted lipid. Morgan *et al.* (1992) also found that the consistency of backfat did not decrease when a supplement of 9·5 g purified fish oil/kg was fed between 25 and 70 kg live weight. In this study the concentration of DHA in outer backfat lipids increased from 0·06 in controls to 0·45 g/100 g in supplemented pigs.

Poultry respond to dietary fish oils in the same way as pigs as the results in Table 8 show. As *n*-3 fatty acid concentrations in muscle increased, those of *n*-6 declined and saturated fatty acid concentrations were unchanged, showing the competition which exists between *n*-6 and *n*-3 fatty acids for inclusion into lipid molecules.

Ruminants

Ruminant fat tissue differs from that of the single-stomached species in containing a higher proportion of saturated and a lower proportion of polyunsaturated fatty acids (Table 1). This results from the hydrogenating action of the rumen bacteria which convert a high proportion of polyunsaturated fatty acids from forage or concentrate diets into saturated fatty acids or unsaturated fatty acids with fewer double bonds. However there are many reported examples of tissue fatty acid composition being changed via the diet, all of which involve manipulation of rumen fermentation patterns.

Table 6. *Effects of feeding 0 or 150 g ground flaxseed/kg diet for 25 d before slaughter on the* n-*3 fatty acid content of backfat and muscle (mg/g tissue) of pigs* (Data from Romans *et al.* 1995*a*)

	Backfat		Muscle	
Fatty acid	0	150	0	150
18:3 (α-linolenic)	10	53	0·19	0·87
20:5 (eicosapentaenoic)	0·09	0·38	0·033	0·031
22:6 (docosahexaenoic)	0·13	0·14	0·017	0·015

Table 7. *Effects of feeding a basal diet (0) supplemented with 60 g refined sardine oil/kg for 28 d on the fatty acid composition (g/100 g total fatty acids) of total lipids in outer layer of backfat and perirenal fat of pigs* (Data from Irie & Sakimoto, 1992)

	Backfat		Perirenal fat	
Fatty acid	0	60	0	60
18:2*n*-6 (linoleic)	10·8	9·8	7·9	7·5
18:3*n*-3 (α-linolenic)	1·9	2·2	1·4	2·1
20:5*n*-3 (eicosapentaenoic)	0·1	1·2	0·1	1·5
22:6*n*-3 (docosahexaenoic)	0·4	1·3	0·6	1·9

Table 8. *Effects of feeding diets containing 0 or 200 g purified fish oil/kg between birth and slaughter (52 d) on the saturated and* n-*3 and* n-*6 polyunsaturated fatty acid composition (g/100 g total fatty acids) of breast and thigh meat in cockerels* (Data from Huang & Miller, 1993)

	Breast		Thigh	
Fatty acid	0	200	0	200
Saturated	35·7	39·6	33·5	34·8
n-3	2·4	10·9	1·4	7·7
n-6	20·5	14·0	20·2	15·5

Work in the 1970s showed that sheep (but not cattle) fed on whole barley produced firmer fat than those fed on rolled or processed barley due to lower concentrations of C7–C18 branched-chain fatty acids (Ørskov *et al.* 1974). These are synthesized from propionic acid whose production is increased when the soluble carbohydrate content of the diet is raised. The relevance of these results to human nutrition is unknown.

The fatty acid composition of concentrate (grain-based) and forage (grass-based) diets are quite different and lead to different fatty acid compositions in tissues. In the study described in Table 9, steers finished on grass had higher concentrations of α-linolenic acid and all other *n*-3 fatty acids than young bulls given a barley–soyabean concentrate diet which had higher concentrations of linoleic acid and all other *n*-6 fatty acids. These results are similar to those obtained by Marmer *et al.* (1984) and are explained by the fact that α-linolenic acid is the major fatty acid in grass lipids whereas cereals and the oil seeds used in concentrate diets are major sources of linoleic acid. A proportion of each of these has clearly avoided breakdown in the rumen. Beef from cattle fed on grazed grass had a much

Table 9. *Fatty acid composition (g/100 g total fatty acids) of muscle* (m. longissimus) *lipid from cattle fed on grass or concentrates* (M. Enser, K. Hallett, B. Hewett, G. A. J. Fursey and J. D. Wood, unpublished results)

Fatty acid	Grass	Concentrates
18:2*n*-6 (linoleic)	2·50	8·28
20:3*n*-6	0·26	0·53
20:4*n*-6 (arachidonic)	0·84	2·32
18:3*n*-3 (α-linolenic)	1·23	0·52
20:4*n*-3	0·19	0·03
20:5*n*-3 (eicosapentaenoic)	0·51	0·20
22:5*n*-3 (docosapentaenoic)	0·76	0·48
22:6*n*-3 (docosahexaenoic)	0·07	0·05

more favourable *n*-6:*n*-3 fatty acids ratio in a recent study (M. Enser, K. Hallett, B. Hewett, G. A. J. Fursey and J. D. Wood, unpublished results; Table 9).

Feeding a high level of sunflowerseed oil (58 g/kg concentrate diet) to sheep caused an increase from 2 to 7 g/100 g in linoleic acid in perirenal fat in one study (Gibney & L'Estrange, 1975) but such high fat concentrations are sometimes associated with poor rumen function and digestibility. More dramatic effects on composition without these undesirable consequences can be obtained if the lipid is encapsulated in protein cross-linked with formaldehyde (Cook *et al.* 1972). By protecting unsaturated dietary fats in this way, concentrations of linoleic acid equivalent to those in pigs can quickly be obtained. Other forms of chemical protection include Ca salts, although this approach is only partly successful in preventing hydrogenation of unsaturated fatty acids.

Natural protection of polyunsaturated lipids can be provided by the seed coat or the intact organelle (e.g. chloroplasts in grasses) within which the lipid is enclosed. Certain types of processing also offer protection. For example, Clinquart *et al.* (1991) demonstrated increased incorporation of α-linolenic acid into perirenal fat of young bulls when steamed flaked linseed was given.

Long-chain polyunsaturated fatty acids from fish oils appear to avoid rumen hydrogenation completely and are absorbed intact in the small intestine (Ashes *et al.* 1992). The results in Table 10 show that when a supplement of protected fish-oil (300 g/kg diet) was given to sheep, EPA and DHA were incorporated into lipids but only into phospholipids. This means that the scope for influencing total lipid (within which phospholipid is a small part except in very lean animals) in ruminants by feeding fish oils is less than in single-stomached animals where EPA and DHA are also incorporated into triacylglycerols (Table 7). Other evidence of efficient incorporation of EPA and DHA into ruminant muscle lipids was given by Dawson *et al.* (1991).

In cattle and sheep there are clear differences in the taste (flavour) of meat produced from either grass- or grain-based diets. In American work the intensity of desirable beef flavour is higher after grain-feeding (Medeiros *et al.* 1987) whereas in New Zealand, where grass feeding is the norm, there is evidence that the flavour of grass-fed lamb is preferred (Table 11). In the work described in Table 11 a third group of sheep were fed with a protected lipid supplement rich in linoleic acid. The flavour of lamb from this group was disliked and in other studies comments such as 'pork-like' have been made about lamb high in linoleic acid (Melton, 1990). All these results show the importance of lipid fatty acid composition in flavour development, with a different range of flavour precursors being produced from saturated, *n*-6 polyunsaturated or *n*-3 polyunsaturated fatty acids. Therefore

Table 10. *Effects of feeding protected fish oil (PFO) to sheep on the fatty acid composition of muscle* (m. longissimus) *lipids (g/100 g total fatty acids)* (Data from Ashes *et al.* 1992)

Fatty acid	Control	300 g PFO/kg
Triacylglycerols		
18:2*n*-6 (linoleic)	2·6	2·3
18:3*n*-3 (α-linolenic)	1·3	0·9
20:5*n*-3 (eicosapentaenoic) 22:6*n*-3 (docosahexaenoic)	ND	ND
Phospholipids		
18:2*n*-6 (linoleic)	23·9	17·1
18:3*n*-3 (α-linolenic)	2·2	0·6
20:5*n*-3 (eicosapentaenoic)	2·4	11·6
22:6*n*-3 (docosahexaenoic)	1·2	3·8

ND, not detectable.

there appears to be considerable scope to change the fatty acid composition of ruminant meats and to make it more acceptable to consumers on grounds of both healthiness and taste.

EFFECTS OF ANTIOXIDANTS

Vitamin E, α-tocopherol, is the major lipid-soluble antioxidant in animal tissues which acts post-mortem to delay oxidative deterioration of the meat. Oxidation manifests as a conversion of the red muscle pigment myoglobin to brown metmyoglobin and the development of rancid odours and flavours from the degradation of the polyunsaturated fatty acids in the tissue membranes. Dietary supplementation with vitamin E increases its deposition in the muscle and fat so that the oxidation is retarded and shelf-life of the meat is enhanced. This occurs not only with single-stomached species such as pigs and poultry, which consume cereal-based diets relatively low in vitamin E, but also in ruminants consuming grass with a naturally high vitamin E content.

The improvement in the oxidative stability of chicken and turkey breast muscle in relation to the vitamin E content of the feed is shown in Table 12 (Marusich *et al.* 1975). Meat from 8-week-old broiler cockerels which had been fed with 16 mg vitamin E/kg feed was incipiently rancid (thiobarbituric acid number >0·75) after 5 d storage whereas meat

Table 11. *Effect of feeding system on eating quality and fatty acid composition (g/100 g total fatty acids) of subcutaneous fat tissue in lambs* (Data from Purchas *et al.* 1979)

	Pasture	Grain	PPFA
Tenderness*	5·6	5·3	3·9
Juiciness*	5·1	5·4	4·0
Flavour*	5·3	4·8	2·8
18:0 (stearic)	28·3	18·9	20·2
18:2 (linoleic)	4·1	5·9	22·9

PPFA, protected polyunsaturated fatty acid supplement.

* Taste panel used hedonic scales of 1–7.

Table 12. *Effect of dietary vitamin E concentration on deposition in poultry breast muscle and the development of oxidative rancidity (thiobarbituric acid (TBA) number) in meat stored at 1·0°* (Data from Marusich *et al.* 1975)

Species	Vitamin E in feed (mg/kg)	Muscle vitamin E (mg/100 g)	TBA number after storage (d)
Cockerels*	16	0·20	0·86 (5)
	40	0·50	0·50 (14)
	60	0·62	0·36 (14)
Turkey hens†	5	0·10	1·64 (7)
	150	0·13	0·81 (7)
	250	0·19	0·62 (7)
	450	0·21	0·39 (7)

* Broilers fed for 8 weeks.
† Supplemental diet fed for weeks 16–20.

from birds fed with 40 or 60 mg/kg feed was not rancid at 14 d. Turkeys responded in a similar manner except that much larger amounts were needed in the feed because of the poor deposition of dietary vitamin E in turkeys compared with chickens.

Supranutritional levels of vitamin E similar to those used for the turkeys not only improve the oxidative stability of pork lipids but maintain the redness of the muscle and decrease drip loss (Table 13; Asghar *et al.* 1991). They can also prevent the excessive drip loss from pale, soft, exudative (PSE) muscle from stress-susceptible pigs (Cheah *et al.* 1995). This action seems to result from decreased membrane phospholipase activity through higher vitamin E content of the tissue membranes. The stability of beef muscle is also improved by supranutritional levels of vitamin E in the animal's feed (Table 14) and as with pork, colour stability and drip loss are improved (Faustman *et al.* 1989). In studies at Bristol, daily supplementation of concentrate diets with 2500 mg vitamin E for 40 d resulted in a 7–10 d extension of colour shelf-life when beef steaks were displayed in modified-atmosphere packs (Taylor *et al.* 1994). The end of shelf-life was indicated by 0·2 metmyoglobin in the muscle surface as predicted from spectrophotometer measurements.

Feeding animals with more unsaturated fatty acids to improve the P:S ratio or feeding *n*-3 polyunsaturated fatty acids as linseed or fish oil to lower the *n*-6:*n*-3 ratio increases the susceptibility of the meat to oxidation. Concomitant increases in dietary vitamin E are therefore necessary to prevent flavour deterioration due to lipid oxidation. Turkeys fed with 20 g tuna oil/kg diet for 9 weeks had normal flavour if vitamin E was included in the feed at 250 mg/kg (Table 15; Crawford *et al.* 1975) but fishy taints developed when lower dietary levels were used. Although the concentrations of polyunsaturated fatty acids in the tissues of the chickens fed with fish oil in the study of Huang & Miller (1993; Table 8) were similar to those of the turkeys, their meat was acceptable when freshly cooked although the basal dietary vitamin E was only 50 mg/kg. However, when the cooked thigh meat was kept refrigerated, rancidity developed and even vitamin E at 450 mg/kg feed was only partially effective in preventing this change since disruption of the muscle structure during cooking increases the rate of development of rancidity. Leskanich *et al.* (1996) found that pigs fed with 10 g fish oil/kg diet from 52–95 kg live weight required 250 mg vitamin E/kg in the feed to maintain chemical and organoleptic measures of acceptability at normal levels.

Table 13. *Effect of supranutritional dietary vitamin E on muscle quality of pork* (Data from Asghar *et al.* 1991)

	Vitamin E supplementation (mg/kg feed)		
	10	100	200
Longissimus muscle vitamin E (mg/kg)	0·5	2·6	4·7
Drip loss (g/kg)*	213	212	141
Colour "a" value*	7·0	7·9	8·7
TBA number *	5·17	2·96	1·33

TBA, thiobarbituric acid.
* Values obtained after storage at 4° for 10 d under fluorescent lights.

Table 14. *Effect of supplemental dietary vitamin E on the oxidative stability of frozen beef patties* (Data from Faustman *et al.* 1989)

Treatment	*Gluteus medius* vitamin E (mg/kg)	TBA number Fresh	TBA number Stored*
Control	1·6	0·11	1·19
+ Vitamin E	4·4	0·13	0·19

TBA, thiobarbituric acid.
* Patties stored at − 18° for 1·5 months.

Table 15. *Effects of dietary fish oil and vitamin E on the fatty acid composition (g/100 g total fatty acids) and flavour of turkey breast muscle* (Data from Crawford *et al.* 1975)

	Treatment			
Fatty acids	BF (40 g/kg)	FO (20 g/kg)	FO + E (20 g/kg)(100 mg)	FO + E (20 g/kg)(200 mg)
18:2*n*-6 (linoleic)	23·7	16·1	15·8	17·1
20:4*n*-6 (arachidonic)	8·2	6·4	5·5	5·8
20:5*n*-3 (eicosapentaenoic)	0·6	4·3	4·4	4·4
22:5*n*-3 (docosapentaenoic)	1·2	1·6	1·6	1·6
22:6*n*-3 (docosahexaenoic)	1·4	15·2	15·0	14·4
Flavour score*	1·96	3·74	3·24	1·99

BF, beef tallow; FO, tuna oil 20 g/kg + BF 20 g/kg.
* Taste panel score, 1 = no fishy flavour, 5 = very fishy flavour.

As already discussed, the different flavours of beef and lamb produced from grass-based or grain-based feeding systems are probably due to the differences in tissue fatty acid composition, especially the *n*-6:*n*-3 fatty acids ratio. It is important to know whether dietary vitamin E supplementation at high levels will affect these flavour variations and current work underway at Bristol is providing information in this area.

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