INVITED LECTURE

ALTERING THE CONTENT OF ESSENTIAL NUTRIENTS IN MEATS?

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Abstract—**Meat from different farm animal species contributes significantly to the intake of several essential nutrients, at least in societies with a high level of meat consumption. Apart from supplying high-quality protein, meat is a valuable source of long chain *n*-3 fatty acids, essential trace elements (cobalt (cobalamin), copper, iron, iodine, manganese, selenium, and zinc), most B-vitamins, and a series of other micronutrients. Knowing the factors that determine the content of essential nutrients in meat is thus of importance to human nutrition and health. The content of essential nutrients in meat depends on many factors and the potential to alter the composition of meat strongly differs according to the nutrient considered. Enhancing the content of long chain *n*-3 fatty acids in meat has been investigated extensively over the last decades. It is now clear that, apart from major differences between species and between muscles and tissues within species, the animal's dietary fatty acid composition has the largest impact on the fatty acid composition of muscle and fat tissue. Genetic tools may also offer some potential to steer the fatty acid composition of meat but this needs additional research. Less research has been devoted to trace elements in meat. In general, increasing the supply of these elements in the animal's diet increases the content in liver, whereas the content in muscle is more conserved. Selenium and iodine contents are much more responsive to increasing levels in the diet than copper, iron, manganese and zinc, due to differences in the major site of homeostatic regulation. The potential of altering the nutrient composition of meat by new feeding and breeding strategies need thus be investigated and evaluated case by case. From a human health point of view, cost-benefit analyses are required that should involve, 1/ quantifying the shift in intake of a nutrient in a specific population in response to altering the nutrient composition of meat, 2/ evaluating the costs and efforts that are needed to alter the composition of fresh meat against alternative strategies, e.g. plant biofortification via fertilizers (e.g. selenium), addition of sources of these nutrients during meat processing, other human nutrition strategies, or enrichment of other non-meat food items.**

***Index Terms* — *n*-3 polyunsaturated fatty acids, trace elements, meat, human nutrition, feed**

I. INTRODUCTION

Meat and meat products contribute significantly to the intake of energy and essential nutrients, at least in societies with a high level of consumption of these food items (Givens, 2005; Givens *et al.*, 2006). There are very large differences between societies in the level of consumption of animal-derived foods and in the types and characteristics of the prevailing animal production systems. Consequently the impact of the production and consumption of animal-derived foods on human health is diverse (FAO, 2009). E.g. the current global average meat consumption is 100 g per person per day, with about a 10-fold variation between high-consuming and low-consuming populations (FAO, 2009). It is expected that the demand for animal-derived foods and meat in particular will continue to grow strongly in the coming decades, especially in developing countries, driven by increasing purchasing power, population growth and urbanisation (FAO, 2009). A much smaller increase is projected for the OECD countries. In addition, the current high levels of consumption of meat have been criticized for contributing to the burden of chronic diseases (World Cancer Research Fund, 2007). Knowing the factors that determine the nutritional value of meat is thus of importance to human nutrition and health.

Apart from supplying high-quality protein, meat is a valuable source of long chain *n*-3 fatty acids, essential trace elements (copper, iron, iodine, manganese, selenium, zinc), most B-vitamins, and a series of other micronutrients (Higgs, 2000). The content of essential nutrients in meat depends on many factors and the potential to alter the composition of meat strongly differs according to the nutrient considered. Enhancing the content of long chain *n*-3 fatty acids in meat has been investigated extensively over the last decades. Less research has been devoted to trace elements in meat. The aim of the present manuscript is to summarize literature information on the contents of long chain *n*-3 fatty acids and several trace elements in meat, and to critically evaluate the potential of animal feeding and breeding strategies to alter the essential nutrient composition of fresh meat.

II. FAT AND ESSENTIAL FATTY ACID CONTENT OF MEAT

For a long time meat has been criticised for its too high fat content and inappropriate fatty acid composition. This has initiated a vast amount of research in the last decades on the lipid and fatty acid metabolism in farm animals and the composition of their products. In meat cuts devoid of external fat, the protein content is relatively constant at approximately 20% on a fresh matter basis, whereas the fat content is more variable and may vary between 1 and 10% depending on species, muscle, nutrition etc. In meat processing, variable amounts of subcutaneous fat are used. Hence, whereas fresh meat is lean in most cases (fat content generally lower than 5%), containing only intra- and intermuscular fat, the fat content of meat products may vary strongly and be as high as over 50% (Chizzolini *et al.*, 1999). Unless a greater proportion of carcass fat depots is directed to feed and non-food applications in future, the consumption of meat and meat products will continue to contribute significantly to the overall energy, fat and fatty acid intake in populations with a large consumption of these products. This also means that reducing the fat content of carcasses contributes to lowering the intake of animal fats, but that the individual consumer has the greatest impact on his animal fat intake through the choice of the food products at purchase.

Since the demand for animal protein has been growing at the expense of animal fat, there has been for a long time and there is still a large interest in the animal industry to increase the protein to fat ratio, particularly in meat-producing animals (Higgs, 2000; Roehe *et al.*, 2003; Wood *et al.*, 2008). Quantitative animal genetic selection has been successfully applied for this purpose in meat producing animals. Muscle protein accretion and body fat accretion in growing animals are negatively genetically correlated, hence it has been possible to select for animals with a high body protein to fat content. In addition, the efficiency of feed to food conversion is higher in the case of protein deposition versus fat deposition. Lean animals do consume less feed than fat animals. Since feed costs are the major cost item in most animal production systems, the economic incentive to genetically select for lean meat producing animals and to optimise feeding systems in terms of balancing nutrient supplies for fast and lean muscle accretion has been great. The Piétrain breed is an example of an extremely lean breed of pigs. The carcass fat to lean ratio in this breed dropped from 0.49 to 0.19 between 1970 and 2000 (Roehe *et al.*, 2003). Classical breeding programmes in farm animals have been very effective in many ways, and although there is still room for progress, it seems that this type of selection starts to face its limits (Rauw *et al.*, 1998). Not only is progress levelling off, side-effects of mass selection for animal productivity are also appearing, such as reduced animal fertility, increased prevalence of metabolic disorders and problems with intrinsic product quality. One example is e.g. the very low intramuscular fat content of lean meats, reducing the flavour and juiciness of cooked meats (Wood *et al.*, 2003). Muscle cuts from very lean animals also seem to have reduced suitability for processing. It is unlikely that conventional animal genetic selection and management strategies will be able to solve these issues. The implementation of new molecular-genetic technologies may offer perspectives in this respect, and their potential should at least be investigated. While allowing making further progress in terms of overall animal productivity, these tools should enable to steer tissue-specific expression of traits, e.g. to produce lean carcasses with higher intramuscular fat content and improved eating quality. However, there is still much research needed before this becomes feasible.

Apart from the gross composition, the fatty acid composition of meat is also matter of intense debate and research. Whereas the amino acid profile of muscle tissue is relatively conserved and difficult to modify, the fatty acid composition of animal products is more susceptible to manipulation. Animal fats strongly differ in fatty acid composition, but are generally considered too high in saturated and too low in polyunsaturated fatty acids (PUFA). On the other hand, apart from the major supply by fish consumption, meat and eggs are the only source of long chain *n*-3 PUFA for the majority of the population in western countries that does not consume fatty fish on a regular basis (Gibbs *et al.*, 2009). There are numerous studies and excellent reviews on the main factors determining the fatty acid composition of meat from different farm animal species. Hence, this information will not be repeated here. The effect of fat deposition in farm animals and the relationship between fat content and fatty acid composition in meat has been reviewed among others by De Smet *et al.* (2004) and Wood *et al.* (2008). The dietary fatty acid supply is the main factor governing the fatty acid composition of intramuscular fat and adipose tissue. This involves the source and content of dietary fat, and the duration and time of feeding. Effects of dietary strategies and fat sources have been discussed by Raes *et al.* (2004) and Wood *et al.* (2003, 2008) for various species, Scollan *et al.* (2001, 2006) and Lourenço *et al.* (2008) for ruminants, and Rymer and Givens (2005) for poultry. Collectively, this can be summarized as follows to our view.

1. The fatty acid composition of adipose tissue and muscle in farm animals depends on the amount of fat in the carcass and in muscle. Effects of diet and genotype have therefore always to be interpreted against the amount of fat. In order to allow evaluating the impact on the human intake of fatty acids, fatty acid composition of meat should always be reported on a tissue basis (mg/100 g sample weight) and not only as proportions of the total lipid fraction, or at least information on the sample total lipid content should be provided.
2. There are important differences between species that can only be partly explained by differences in the digestive process. Because of the intense lipolysis and biohydrogenation taking place in the rumen, fats from ruminant

animals are generally much higher in saturated fatty acids and lower in PUFA compared to fats from monogastric animals. In addition, there are differences between species in the deposition of (long chain) PUFA in adipose tissue versus muscle. Ruminants deposit PUFA mainly in muscle whereas concentrations of PUFA are more similar for adipose tissue and muscle in pigs. Long chain (C20-22) PUFA are found in adipose tissue and muscle neutral lipid in pigs and sheep but much less so in cattle.

3. In monogastric species, dietary fatty acids undergo little transformation during digestion and absorption. Hence, the fatty acid composition of tissues is a mirror of the dietary fatty acid composition in these species. On the other hand, products from ruminants do contain a series of minor fatty acids such as trans fatty acids, conjugated linoleic and α-linolenic fatty acids (CLA and CLNA) and odd and branched chain fatty acids, resulting mainly from rumen microbial biohydrogenation and metabolism. The beneficial or adverse human health effects of these minor fatty acids is still unclear and will differ for each of these specific fatty acids. Consequently, the effects of the regular intake of foods containing these fatty acids is also not well established at present.
4. The dietary supply of α-linolenic acid (ALA, C18:3 *n*-3) increases the content of ALA and total *n*-3 PUFA in muscle and adipose tissue. The increase in total *n*-3 PUFA mainly results from the increase in ALA and to a much lesser extent from increased concentrations of the long chain derivatives eicosapentaenoic acid (EPA, C20:5 *n*-3), docosapentaenoic acid (DPA, C22:5 *n*-3) and docosahexaenoic acid (DHA, C22:6 *n*-3). Indeed, as in humans, the elongation and desaturation of ALA to long chain *n*-3 PUFA is limited in farm animals. Particularly the final synthesis of DHA is limiting, resulting mostly in no or a low increase in DHA content in meat from animals fed diets rich in ALA. Again, there are species differences with broilers being more efficient than other species in this respect (Poureslami *et al.*, 2010).
5. A large increase in the content of long chain *n*-3 PUFA in meat requires the direct supply of these long chain *n*-3 PUFA by means of fish oil/meal or micro-algal oil/biomass incorporation in the diet. Due to declining fish oil supplies and the rising need for long chain *n*-3 PUFA in the aquaculture industry, the use of micro-algae as the primary producers of long chain *n*-3 PUFA in livestock diets is a more desirable and sustainable strategy in the long term (Givens and Gibbs, 2006; Brunner *et al.*, 2009). The major advantage of the use of micro-algae is that these can be cultivated. The deposition of DHA in tissues is as effective when using micro-algal biomass compared to fish oil (Rymer *et al.*, 2010, broilers; Vossen *et al.*, 2010, pigs). A general concern when using long chain PUFA in the diet of farm animals is the negative effect on the oxidative stability and flavour of meat. Fish oil in the diet above certain levels leads to off-flavours and reduced fat stability. High levels of antioxidants are able to retard oxidative rancidity, but do not allow to overcome the problem entirely. Processed meat products, particularly fat-rich fermented meat products, are much more sensitive to oxidative deterioration compared to fresh meats. More work is required in this area to produce meat and meat products with an improved composition without compromising sensory quality. Much depends on the levels of long chain PUFA used in the diet and appearing in the meat. In a recent study in pigs, we did not find negative effects on the sensory properties of fresh meat and dry-cured ham from including fish oil and micro-algal biomass in the diet of pigs at modest levels that however resulted in significant increases in the content of long chain *n*-3 PUFA (Vossen *et al.*, 2010). In poultry, Rymer *et al.* (2010) similarly reported that the use of algal biomass and fish oil did not result in differences in oxidative stability.
6. Although ruminants offer less potential than monogastric animals for contributing to the human intake of long chain *n*-3 PUFA, the abundant supply of ALA in grass-based systems is a sustainable opportunity that should be explored. Particularly the benefits and specific effects of botanically diverse pastures needs more investigation. Searching for new methods of protecting PUFA from biohydrogenation in the rumen also remains of paramount importance. Overall, the feeding strategies that have been studied in the past for increasing the content of beneficial fatty acids do generally not rise the feed cost enormously and do have no negative impact on animal performances and welfare when recommended levels of dietary fat are respected.

Genetic tools have been investigated much less compared to nutritional strategies. However, there is significant genetic variation for fatty acid deposition and metabolism. In pigs, moderate to high heritabilities were found for the proportions of intramuscular PUFA, and for ratios of fatty acids that reflect the *n*-6 and *n*-3 long chain fatty metabolism (Ntawubizi *et al.*, 2010). This offers opportunities for genetic selection. However, the phenotypic and genetic correlations between the proportions of PUFA in meat and carcass lean meat content or intramuscular fat content are negative. Mass selection for lean carcasses thus results in higher proportions of PUFA in meats. On the other hand, this is accompanied by lower levels of intramuscular fat, reducing the PUFA content in a meat portion and hence also the contribution to human intake. Further lowering the intramuscular fat of pork is also not warranted because of the negative impact of too low levels of intramuscular fat on meat flavour. It seems that molecular-genetic approaches will be required to differentially affect the levels of carcass and intramuscular fat, and to steer the fatty acid composition favourably at the same time. As an example, the functional expression of a delta-12 fatty acid desaturase gene from spinach in transgenic pigs was reported by Saeki *et al.* (2004), resulting in levels of linoleic acid that were approximately 10-fold higher in adipocytes differentiated in vitro and approximately 20% higher in backfat in vivo.

This was the first time a plant gene was expressed in a complex mammalian system. The generation of cloned pigs that express a humanized *Caenorhabditis elegans* gene, fat-1, encoding an *n*-3 fatty acid desaturase is also reported (Lai *et al.*, 2004). Alternatively, research is going on in plant molecular science aiming at the expression of several desaturase and elongase enzymes in rapeseed, which should result in plant-derived foods containing long chain *n*-6 and *n*-3 PUFA (Venegas-Calerón *et al.*, 2010). These long chain derivatives are normally absent in plant material. Hence, different approaches may become available in the long term to improve the supply of long chain *n*-3 fatty acids. It remains to be evaluated which approach offers the best potential and has the greatest chance of being successful.

III. TRACE ELEMENTS COMPOSITION OF MEAT

Essential trace elements (cobalt (cobalamin), copper, iron, iodine, manganese, selenium, zinc) are functional, structural, and regulatory components of numerous biomolecules in the living organism. The intake of several essential trace elements is still suboptimal in many countries around the world. Low- and middle-income countries are most affected, but the prevalence of e.g. iron and iodine deficiency is also high in high-income countries (Black *et al.*, 2008; WHO, 2004, 2008). Meat is a good carrier of several essential trace elements, providing these elements mostly in an organic, well-absorbable form. Hence, similarly to essential fatty acids, increasing or optimising the content of essential trace elements in meat might positively contribute to human health. The homeostatic regulation and metabolism of essential trace elements is, however, complex and differs according to the element (Windisch, 2002). To maintain metabolic equilibrium, absorption and excretion of essential trace elements is actively adjusted in relation to changes in intake. The regulation of some trace elements occurs mainly at the site of absorption (e.g. copper, iron, manganese, zinc), whereas for others renal excretion is the major site of regulation (e.g. cobalt, iodine, selenium). Consequently, the potential to alter the content of essential trace elements will strongly depend on the element and all factors interfering in the regulation and metabolism. These include the source, content and chemical species of the element in the diet, and interfering dietary and metabolic factors. The most important dietary factors that interfere are chelating agents, that may inhibit as well as promote bioavailability, and metal ion (e.g. calcium) and other trace element interactions that are mostly inhibiting absorption and bioavailability.

In a recent project funded by EFSA, we reviewed the literature on concentrations of essential trace elements in edible tissues and products, linked with the dietary supply of various concentrations and forms of the element (Van paemel *et al.*, 2010). A summary is given in Table 1 for muscle and liver contents. The range of treatment mean contents are presented in relation to the range of feed contents that were applied, across species, type of animals, duration of the feeding treatment and chemical forms of the element. The lowest values mostly, but not always, correspond to basal treatments in which no extra supplementation was provided and the trace element supply was limited to the background concentrations in the feedstuffs. These were not always analysed and were then set to zero. Hence, values for the feed element content, at least in the lower range, might be underestimated. Tissue element contents were either recorded on a wet or dry matter tissue basis. Values are presented here on a wet tissue basis, assuming 25% dry matter in muscle and liver.

Table 1. Range of treatment mean values for trace elements contents in muscle and liver across species (pigs, ruminants, poultry). Treatments involve dietary supplementation with various doses and forms of the element. References used for compilation of the data in this table can be found in Van paemel *et al.* (2010).

	# treatments (studies)	**Range in feed content (mg/kg DM)**	**Range in tissue content (mg/kg wet tissue)**
Muscle			
Cobalt	12 (2)	0.2 – 66.8	0.012 – 0.130
Copper	12 (3)	0 – 488	0.43 – 1.38
Iodine	26 (6)	0 – 100 (11.1)[1]	0.0034 – 0.312 (0.096)[1]
Iron	20 (5)	44.4 – 5000	8.3 – 35
Manganese	34 (6)	0.4 – 8920	0.02 – 0.94
Selenium	43 (9)	0 – 42.3	0.07 – 27
Zinc	8 (2)	132 – 3659	11.8 – 29.8
Liver			
Cobalt	22 (5)	0 – 600	0.050 – 3.18
Copper	43 (5)	0 – 842	3.2 – 160
Iodine	19 (4)	0 – 11.1	0.0075 – 0.225
Iron	27 (7)	44.4 – 5000 (2000)[2]	30 – 1088 (326)[2]

Manganese	59 (10)	0.4 – 8920 (5038)[3]	0.63 – 158 (19.3)[3]
Selenium	36 (8)	0 – 42.3	0.33 – 133
Zinc	73 (10)	23 – 3659	17.9 – 471

[1] Between brackets the value for two treatments with a high feed content (100 mg/kg DM) resulting in a high muscle content (279 and 312 mg/kg) excluded.

[2] Between brackets the value for one treatment (5000 mg/kg DM) resulting in a high liver content (1088 mg/kg) but no effect on the muscle content excluded.

[3] Between brackets the value for two treatments resulting in a very high liver content (158 and 58 mg/kg) excluded.

For copper, iron and manganese concentrations are manifold higher in liver than in muscle. Basal concentrations of these elements are roughly 5 to 10 fold higher in liver than in muscle. In muscle, the response to increased dietary concentrations is mostly absent. In liver, the response is highly variable among studies, but the content mostly increases with increasing dietary supply. The chemical form of the element in the supplement (e.g. inorganic or organically bound) does not appear to affect the response. Similarly, a response is observed for the liver zinc content with increasing dietary supply of zinc but with great variability among studies. A limited number of studies also provide evidence that there is no effect of dose and chemical form of supplementation on the muscle zinc content. Data from other food studies indicate a range in mean values for zinc content between 10 and 67 mg/kg muscle (n=50) and between 14 and 103 mg/kg liver (n=20) across species and types of muscle, hence showing similar or slightly higher values for liver compared to muscle.

The contents of iodine and selenium are roughly 2 to 3 fold higher in liver than in muscle. In contrast to the other elements, there is a clear response in both liver and muscle for these elements to increasing dietary concentrations. The source of the element is also important. For iodine, most studies have used an inorganic source. In one study, supplementation with potassium iodide was compared with supplementation of the algae *Laminaria digitata* at similar doses of iodine (He *et al.*, 2002). The organic source resulted in approximately a 1.5 and 2 fold higher liver and muscle content respectively compared to the inorganic form. Dierick *et al.* (2009) reported an approximately 3.5 and 4.5 fold increase in muscle and liver iodine content in piglets after adding 9 mg iodine/kg feed from the seaweed *Ascophyllum nodosum* to a diet containing a basal content of 1 mg iodine/kg. For selenium, several studies in different species are available in which supplementation with sodium selenite was compared with Se-enriched yeast. Both the inorganic and organic source result in increased deposition of selenium in liver and muscle, but the response to selenium-enriched yeast is approximately 2 fold higher compared to sodium selenite (EFSA, 2008).

Cobalt is a particular trace element since its only known function is as an essential component of vitamin B_{12}. Humans and monogastric animals (excluding horses and rabbits) do not require cobalt but they require vitamin B_{12}. Consequently, there is no need for any cobalt supplementation to their feed. The ruminant microflora can synthesize vitamin B_{12}, provided dietary cobalt is available in sufficient quantities. Consequently the vitamin B_{12} requirement of these animals can be covered by dietary cobalt. Animal foods (i.e., meat, milk, egg, fish, and shellfish) but not plant foods are considered to be the major dietary sources of vitamin B_{12} (Truswell, 2007; Watanabe, 2007). Vegetarians and particularly vegans are thus susceptible to vitamin B_{12} deficiency. In the few studies that are available, increased cobalt concentrations in the feed resulted in increased cobalt contents in both muscle and liver. More important is the response of variable dietary cobalt concentrations on the vitamin B_{12} content of edible animal products. This was investigated by Ortigues-Marty *et al.* (2005) in beef and lamb. The animals were supplemented in trace elements according to usual feeding practices in France in order to theoretically avoid any risk of deficiency. Cobalt allowances varied widely among treatments from (sub-)deficient to plethoric allowances (36 – 2565 µg/kg feed DM) and influenced vitamin B_{12} contents of the liver, and muscles, the latter only in case of deficiency. Surprisingly, an oxidative type muscle (*Rectus abdominis*) showed contents which were double those in glycolytic type muscle (*Semitendinosus*), 10.8 versus 5.0 µg/kg respectively. These values for vitamin B_{12} contents of raw muscles were lower than the values indicated in food composition tables for cooked meat (10 to 30 µg/kg), considering also that there is a loss of this vitamin during cooking (Truswell, 2007; Watanabe, 2007). In liver, vitamin B_{12} contents are manifold higher (0.25 – 1.1 mg/kg) (Ortigues-Marty *et al.*, 2005; Truswell, 2007).

It should be kept in mind that the maximum values of the feed element content reported in Table 1 stem from bioavailability or tolerance studies and all exceed the maximum legally allowed content in complete feedingstuffs in the EU and in Canada. The maximum allowed total feed content in the EU for animals destined for slaughter is 2, 25 – 35, 750, 10, 150, 0.5 and 150 mg/kg feed for cobalt, copper, iron, iodine, manganese, selenium, zinc respectively. Levels that are currently recommended and used in feeds in the EU in order to meet the animal requirements vary according to animal category and are either considerably lower (e.g. iron, iodine, manganese) or close to the maximum allowed content (e.g. selenium). This means that the potential enrichment of animal foods above average current contents through increasing the content of trace elements in the animals' diets differs by element. Given the poor response in muscle to changes in the dietary levels for most elements, the greatest potential thus exists for iodine and for selenium in case an organic source is used.

IV. IMPACT OF ALTERING THE MICRONUTRIENT COMPOSITION OF MEAT ON HUMAN HEALTH

The contribution of food items to the intake of total and specific fatty acids is the resultant of the food item intake, its fat content and its fatty acid profile. Similarly, the contribution of meat to the total intake of essential trace elements is the resultant of the level of consumption of the food item and the element content of the food item. This means that those foods, and in the present case those meats, that are consumed in the largest quantities, are the most appropriate target foods for enrichment. Givens and Gibbs (2008) have given a summary of studies that have estimated the EPA+DHA intake in various countries. A large variation between countries and studies is apparent, but mean intake values are mostly far below the recommended intake values (e.g. current UK recommendation for adults of 450 mg EPA+DHA/d). In addition, there is a lack of normality in the distribution of the intake across populations. In Europe the majority of the population consume considerable less than the mean intake, especially young adults since many of them never eat oily fish. These authors have also estimated the impact on the human intake of long chain *n*-3 PUFA following a shift in the meat fatty acid profile due to alternative animal feeding regimens (Givens and Gibbs, 2008; Gibbs *et al.*, 2009). Adding fish oils to the diets of all farm animals has the potential to provide to the UK adult diet a daily intake of EPA+DHA of about 230 mg, with poultry meat providing the largest amount (74 mg). Although poultry meat offers thus good perspectives, it is clear that modifying only meat, and evidently meat from one species only, will not result in the desired shift in intake of long chain *n*-3 PUFA. In addition, as mentioned above, making increased use of fish oils in farm animals' diets is not sustainable (Brunner *et al.*, 2009). Alternative approaches should therefore be envisaged, e.g. exploitation of micro-algal biomass, genetic selection or modification of animals and genetic modification of certain plants to allow them to synthesize the long chain *n*-3 PUFA (see above). Obviously, a more widespread use of the precursor ALA in animals' diets will likely not raise sustainability concerns. The effect on the human supply of long chain *n*-3 PUFA will then depend on the conversion efficiency of ALA to the long chain *n*-3 PUFA in farm animals yielding increased levels of these derivatives in the animal-derived foods, and on the conversion in humans following the increased intake of ALA from these animal-derived foods. Although the conversion efficiency is low in both farm animals and in humans and the benefits are relatively low, this strategy should nevertheless be encouraged as long as no other sustainable alternatives are available, in view of the large shortage in intake of long chain *n*-3 PUFA and the ease of application (De Henauw *et al.*, 2007).

Regarding the trace elements, as mentioned above, iodine and selenium are the most responsive elements for enriching meat. Based on the iodine enrichment that was achieved in pork following addition of seaweed to the pigs' diet, Dierick *et al.* (2009) estimated the increase in human intake of iodine for Belgium assuming all pork, beef and poultry would be similarly enriched. This simulation showed that the daily intake of iodine from meat via enrichment could increase 4 fold from approximately 4.5 to 17.5 µg/d, increasing the total iodine intake from approximately 70 to 83 µg/d. Milk and dairy products are the main source of iodine intake, followed by meat and bread. Total iodine intake was still far below the recommended intake of 150 µg/d. Hence, iodisation of feedstuffs for meat-producing animals might induce an indirect but substantial, stable and easily controllable contribution to the human iodine supply, without risk for overdosing or the need for shift in eating pattern, but iodine enrichment of meat from a single animal species will not substantially contribute to increasing the human iodine supply. Similar calculations could be done for Se. It is important to mention in this respect that iodine, like selenium, have a narrow range (1:4) between human requirements and tolerable upper intake levels. Although it is very well known that iodine enrichment is more effective via milk and eggs, the allowed maximum contents in mixed feed for dairy cows and laying hens were reduced from 10 to 5 mg/kg feed across the EU in order to minimize the risk of exceeding an upper limit of iodine intake for humans. Compared to other tissues and excreted products (milk and eggs), muscle is thus more resistant to modification but at the same time safer in terms of risk of overdosing.

The limited potential for enriching meat in other essential trace elements by feed supplementation, as mentioned above, means that the contribution of meat to the total human intake of these elements in a population depends on the background element content in meat and the level of meat consumption. There might be other sources of variation in meat trace element content, e.g. species differences, differences in iron content between red and white muscle fibre types etc. Precise estimates of the impact of shifts in meat consumption pattern on the intake of trace elements are lacking. E.g. the actual trend for decreasing beef and increasing poultry consumption in many countries might be expected to aggravate iron deficiency. Likewise, the level of organ meat (liver, kidney) consumption widely differs among countries and populations. The content of trace elements in these meat types is substantially higher than in striated muscle, hence the contribution of organ meat to the total intake of trace elements and vitamin B12 from meat overall is probably not negligible in spite of the lower level of consumption of these meat types.

To allow successful introduction of improved meats in the market, intervention studies might be needed that examine the effect of these foods on human metabolic parameters and that may support potential nutrition or health claims. Only few studies are available in this respect for meat, but there are indications that altered meat may indeed have a positive impact on health indicators. Stewart *et al.* (2001) tested the hypothesis that modified pork with a high content of PUFA and a low content of saturated fatty acids would lower plasma LDL concentrations in women. The modified pig ration was supplemented with soybean oil, hence rich in *n*-6 PUFA, at 40% of the total energy in the ration from soybean oil. The human diet containing modified pork lowered total plasma and LDL cholesterol, and also resulted in shifts in the fatty acid composition of different blood lipid fractions. Weill *et al.* (2001) compared the plasma and erythrocyte fatty acid profile of healthy volunteers that consumed animal products from livestock fed linseed in the diet and livestock fed a standard diet. Linseed was included at 5% in the livestock diets. Without any change in consumers' eating habits, foodstuffs from animals fed linseed diets induced significant modifications in plasma and erythrocyte fatty acid composition. Plasma ALA as well as the long chain derivatives and conjugated linoleic acids increased in the experimental group. Similarly, erythrocyte EPA and DHA increased. The same research groups recently reported on a comparable setup using products from linseed fed animals in overweight volunteers (Legrand *et al.*, 2010). The experimental diet was rich in animal fat with a low PUFA/saturated fatty acid ratio but a low *n*-6/*n*-3 ratio also. The control diet provided less animal fat and both diets excluded seafood. Erythrocyte ALA, EPA and DHA increased in the experimental group and decreased in the control group during the 90 days trial, and this difference was significant. Weight and BMI was reduced in both groups but this difference was not significant. Interestingly, 150 days after the end of the trial a significant weight gain was observed in the control group, whereas this was not the case in the experimental group. No differences between the groups were observed for plasma total, HDL and LDL cholesterol and for plasma triacylglycerols. Larger effects could have been expected if long chain *n*-3 PUFA would have been added to the animals' diets. This was tested by Coates *et al.* (2009). Pork was enriched in long chain *n*-3 PUFA by including a fortified tuna fishmeal product in the pig finisher diets. Healthy volunteers received a selection of five fresh cuts totalling 1000 g/week for 12 weeks from either *n*-3 enriched pork or regular pork, corresponding to an intake of 1.3 g long chain *n*-3 PUFA per week. Compared with the control group, serum triacylglycerols decreased to a greater extent in the *n*-3 group and serum thromboxane production increased to a lesser extent. The authors concluded that modest increases in long chain *n*-3 PUFA intake resulting from regular consumption of enriched pork could improve cardiovascular risk factors.

More generally, cost-benefit analyses are required to establish the opportunity of altering the essential nutrient composition of meat and animal-derived foods in general by new breeding and feeding strategies versus alternative approaches at the level of the food processing industry (e.g. Muguerza *et al.* (2004), Jimenez-Colmenero (2007), Íñiguez de Ciriano *et al.* (2010)), or public health services. It is clear that implementing relatively simple feeding strategies in meat producing systems may offer some benefits to human health, but the potential of modifying meat alone should not be overestimated.

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