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REVIEW ARTICLE

Producing selenium-enriched eggs and meat to improve the selenium status of the general population

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Abstract
The role of selenium (Se) in human health and diseases has been discussed in detail in several recent reviews, with the main conclusion being that selenium deficiency is recognised as a global problem which urgently needs resolution. Since selenium content in plant-based food depends on its availability from soil, the level of this element in food and feeds varies among regions. In general, eggs and meat are considered to be good sources of selenium in human diet. When considering ways to improve human selenium intake, there are several potential options. These include direct supplementation, soil fertilisation and supplementation of food staples such as flour, and production of functional foods. Analysing recent publications related to functional food production, it is evident that selenium-enriched eggs can be used as an important delivery system of this trace mineral for humans. In particular, developments and commercialisation of organic forms of selenium have initiated a new era in the availability of selenium-enriched products. It has been shown that egg selenium content can easily be manipulated to give increased levels, especially when organic selenium is included in hen's diet at levels that provide 0.3–0.5 mg/kg selenium in the feed. As a result, technology for the production of eggs delivering ≈50% (30–35 µg) of the human selenium RDA have been developed and successfully tested. Currently companies all over the world market selenium-enriched eggs including the UK, Ireland, Mexico, Columbia, Malaysia, Thailand, Australia, Turkey, Russia and the Ukraine. Prices for enriched eggs vary from country to country, typically being similar to free-range eggs. Selenium-enriched chicken, pork and beef can also be produced when using organic selenium in the diet of poultry and farm animals. The scientific, technological and other advantages and limitations of producing designer/modified eggs as functional foods are discussed in this review.

Keywords: *Eggs; human nutrition; functional foods; selenium*

Introduction

The relationship between diet and human health has received substantial attention in the last few years, with the realisation that unbalanced diets can cause serious health-related problems. However, not everyone consumes the same food, and people meet their nutritional needs in many and varied ways. From the many food ingredients commonly present in our diet, natural antioxidants are considered particularly important. It is well known that free radicals produced under both normal physiological conditions and under stress conditions can have damaging effects on polyunsaturated fatty acids, DNA and proteins in the body. Antioxidant protection is vital for prevention or substantial reduction in damage caused by free radicals and the products of their metabolism.

Food provides a major source of natural antioxidants for humans, including vitamin E, carotenoids, flavonoids and selenium (Se). Particular interest in selenium has been generated as a result of clinical studies showing that dietary supplementation with organic selenium, in the form of yeast grown on a media enriched with this trace element, decreased cancer mortality two-fold (Clark et al., 1996). Additionally, there are data indicating that inadequate selenium consumption is associated with poor health, genetic defects, decreased fertility and defence against various viral and bacterial diseases (Surai, 2006). Unfortunately, in many countries all over the world human food ingredients can contain inadequate levels of selenium, and selenium deficiency in human nutrition is a global problem. As a result,

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finding solutions to this problem is now on the agenda of many government health bodies.

Results derived from various research studies conducted over the last few years have indicated that the enrichment of animal-derived foods (mainly meat, milk and eggs) with selenium via supplementation of animal feeds can be an effective way of increasing human selenium status in countries where selenium consumption falls below the Recommended Daily Allowances (RDA), e.g. consumption in the UK is shown to be about 50% of the RDA.

Selenium and human health

There is a great body of evidence that shows the health-promoting properties of selenium. Deficiency in the human population is associated with two diseases (Keshan disease and Kaschin-Beck disease) reported in areas of China and other countries characterised by an extremely low selenium content in the soil and in the food chain. In humans, selenium deficiency is associated with a compromised immune system and increased susceptibility to various diseases, including arthritis, cancer, cardiovascular disease, cataracts, cholestasis, cystic fibrosis, diabetes, immunodeficiency, lymphoblastic anaemia, macular degeneration, muscular dystrophy, stroke and some others (Surai, 2006).

The most compelling evidence exists in relation to the cancer-protective effects of selenium (Nadiminty and Gao, 2008; Gromadzinska et al., 2008; Papp et al., 2007; Squires and Berry, 2006; Rayman, 2005; Whanger, 2004). In epidemiological observations and prospective studies, an inverse correlation, between selenium levels in food and blood and the risk of cancer and cancer mortality, was observed. There are also case-control studies showing that selenium levels in blood, serum, hair or toenails are lower in cancer patients than in unaffected people. Thirdly, laboratory animal studies have shown a protective effect of various forms of selenium against cancer initiation and development. Finally, there are human intervention trials showing selenium supplementation to be an effective means of decreasing the risk of DNA damage associated with the development of cancer. So far there have been 10 human trials testing protective effects of selenium against cancer, six of them conducted in China, a country characterised by a number of selenium-deficient regions. The main outcome of the trials was a protective effect of selenium (in most cases selenised yeast) against cancer (Surai, 2006). Such data provided a strong incentive to design a definitive trial for selenium and vitamin E with prostate cancer as a primary end point. Hence, there are new human trials underway to further substantiate the protective effects of selenium against cancer, including a SELECT trial employing 32,000 participants, without prior evidence of prostate cancer, from more than 400 participating study sites in the USA, Puerto Rico and Canada. This trial was planned to last for 12 years with a budget exceeding 200 million US$ (Klein et al., 2003). However, there was a potential problem with this study, since in previous studies a natural product, selenium-enriched yeast, was used, while in the SELECT trial, purified selenomethionine (Se–Met) is being used, and so there are some questions as to how the results of this study can be extrapolated to intakes of selenium through food (Finley, 2005). Furthermore pure Se–Met is not a stable compound and can easily be oxidised, and its protective effect can be compromised. It seems likely that this was the case in this study which was prematurely stopped in October 2008 after the independent review of the results.

In the aforementioned trials, it has been shown that increasing selenium consumption to provide concentrations in the blood exceeding 121 μg/L may address selenium deficiencies and simultaneously provide some protection against cancer. It is not clear at present how this protective effect of increased selenium concentrations in plasma occurs. In general, there are two approaches: nutritional and pharmacological, in order to achieve selenium-protective effects against cancer. The nutritional approach includes consumption of selenium-enriched food, such as eggs, meat and milk, as well as various vegetables. The pharmacological approach involves the consumption of selenium tablets in the form of sodium selenite, Se–Met and various chemically synthesised organo-selenium compounds (Surai, 2006). It should be mentioned that increased selenium status results in not only a cancer-protective effect, but will also help the body fight other free-radical-associated diseases.

Dietary deficiencies of selenium have been implicated in the aetiology of cardiovascular diseases (CVD). However, the results of longitudinal studies within populations conflict with investigations that have shown a relationship between low serum-selenium levels and the risk of coronary disease, while others did not. In general, dietary selenium supplements may be considered anti-atherosclerotic. It has been shown that non-limiting selenium availability counteracts the post-prandial formation of the atherogenic form of low-density lipoprotein (LDL), and provides a rationale for the epidemiological evidence for the inverse correlation between selenium intake and the incidence of chronic and degenerative diseases (Natella et al., 2007). Furthermore, selenium supplementation (200 μg/day as selenium-yeast for a week) has been shown to improve blood fluidity, by metabolic modification of lipoproteins (Abdulah et al., 2006) which may provide an additional protective factor against CVD development. As such, dietary selenium supplementation may provide a safe and convenient method for increasing antioxidant protection in aged individuals, particularly those at risk of ischaemic heart disease, or in those undergoing clinical procedures involving transient periods of myocardial hypoxia (Venardos and Kaye, 2007). Initiation of an atherosclerotic lesion requires endothelial expression of adhesion molecules. Atherosclerosis is accelerated in diabetic patients. This is at least partially caused by hyperglycaemia and hyperinsulinaemia increasing adhesion molecule expression. It was shown that selenium inhibited high-glucose-induced and high-insulin-induced expression of adhesion molecules (Zheng et al., 2008). Therefore, selenium may be considered as a potential preventive intervention for diabetes-accelerated atherosclerosis.

Clearly, the results of clinical studies suggest that an increase in the intake of selenium is associated with health benefits. However, the present focus should be on diagnosing and treating selenium deficiency resulting from a poor diet or disease. Data are being actively accumulated to indicate that selenium deficiency is related to reproductive disorders in man, including poor semen quality and pregnancy complications, and that selenium dietary supplementation may potentially prevent these changes. In addition, selenium supplementation during pregnancy and in the postpartum period reduced thyroid inflammatory activity and the incidence of hypothyroidism (Negro et al., 2007).

Optimal selenium status has been shown to be beneficial in asthma, rheumatoid arthritis, cystic fibrosis, HIV, pancreatitis, brain and neurodegenerative disorders. Recently it was shown that low serum selenium is independently associated with anaemia among older women (Semba et al., 2007). Increased selenium status may also substantially decrease the negative effects of ingested heavy metals (Watanabe, 2002).

Selenium is protective against oxidising radiation (e.g. UV) and can be considered as an anti-ageing agent. For example, low plasma selenium was independently associated with poor skeletal muscle strength in community-dwelling older adults in Tuscany (Lauretani et al., 2007). Similarly, low serum selenium concentrations were associated with poor grip strength among older women (Beck et al., 2007). Furthermore, sub-optimal selenium status may worsen muscle functional decrements subsequent to eccentric muscle contractions (Milias et al., 2006). In elderly people in Spain, serum selenium was associated with self-perceived health, chewing ability and physical activity. In particular, subjects in the upper tertile of serum selenium had more than twice as much probability of reporting good health status, chewing ability and of doing more than 60 minutes of exercise/day.

Low serum concentrations of selenium can be used as a predictor of subsequent disabilities associated with ageing (Bartali et al., 2006). Improved selenium status has been associated with a reduced risk of osteoporotic hip fracture in elderly subjects (Zhang et al., 2006). In the elderly population, those with the lowest selenium levels had a significantly higher risk of mortality over a period of five years (Walston et al., 2006). Similar conclusions were drawn from another study (a nine-year longitudinal study with six periods of follow-up). During the two-year period from 1991 to 1993, 1389 men and women born between 1922 and 1932 were recruited. The effects of plasma selenium at baseline on mortality were determined. During the nine-year follow-up, 101 study participants died. Baseline plasma selenium was higher in individuals who were alive at the end of the follow-up period than in those who died before this time point (Akbaraly et al., 2005). It was also shown that elderly women living independently in the community who have higher serum selenium are at a lower risk of death (Ray et al., 2006). It seems likely that low plasma selenium may be an independent predictor of mortality among older adults living in the community. For example, 1042 men and women of 65 years or older were investigated in the Chianti region of Tuscany, in Italy (Lauretani et al., 2008). Plasma selenium was measured at enrolment (1998–2000), and vital status was ascertained until May 2006. During follow-up, 237 participants (22.7%) died. At enrolment, mean plasma selenium concentrations among participants who survived or died were 0.96 and 0.87 μmol/L ($p < 0.0001$), respectively. The proportion of participants who died, from the lowest to the highest quartile of selenium, was 41.3, 27.0, 18.1 and 13.5% ($p < 0.0001$). After adjusting for age, sex, education and chronic diseases, adults in the lowest quartile of plasma selenium at enrolment had significantly higher mortality compared with those in the highest quartile.

The selenium status of the elderly is related to quality of life. For example, recent results of a cross-sectional survey of 2000 rural Chinese, aged 65 years or older from two provinces in the People's Republic of China, support the hypothesis that a life-long low selenium level is associated with lower cognitive function (Gao et al., 2007). Indeed, in the elderly, cognitive decline was associated with decreases of plasma selenium over time. Among subjects who had a decrease in their plasma selenium levels, the greater the decrease in plasma selenium, the higher the probability of cognitive decline (Akbaraly et al., 2007).

Addressing selenium deficiency in humans via selenium-enriched eggs

The RDA for selenium in the USA is 55 μg/day for adult males and females and in the UK it is 75 μg/day for men and 60 μg/day for women. However, in many countries worldwide the selenium consumption is below those recommended levels.

Since the selenium content in plant-based food depends on its availability from soil, the level of this element in human foods varies among regions. When considering ways to improve human selenium intake, there are several potential options, including the production of selenium-enriched eggs, meat and milk (Surai, 2000, 2002, 2006) as well as selenium supplements in tablet/capsular form.

Several important factors must be considered when choosing the best food supplementation strategy for a given population. Such factors are shown in Table 1. In general, the main sources of dietary selenium differ between different countries. For example, currently in the UK meat and meat products provide 32% of daily selenium consumption, and dairy products and eggs are responsible for 22% of selenium consumption (British Nutrition Foundation, 2001). On the other hand, in Russia about 50% of selenium in the diet originates from bread and cereals, while meat, milk and eggs provide about 20%, 10% and 5% of daily selenium consumption, respectively (Golunkina et al., 2002). In the USA, beef, white bread, pork, chicken and eggs account for half of the selenium in the diet (Schubert et al., 1987). In Ireland, meat and meat products (30%), bread and rolls (24%), fish and fish products (11%), and milk and yoghurt (9%) were the main contributors to mean daily selenium intake (Murphy et al., 2002). In Japan in the alpine communities, fish makes the largest contribution to dietary selenium intake (48% of daily total), followed by eggs (24%) and meat (17%). In the coastal community, fish accounts for 58% of daily total selenium intake, followed by meat (18%) and eggs (16%). In both districts, the total contribution of rice and wheat products was around 10% (Miyazaki et al., 2004).

Among animal-derived products, the egg is ideally suited to meet the requirements mentioned in Table 1. It is a traditional and affordable food in most countries and is consumed by people of all ages more or less regularly, and in moderation. It is also a very safe vehicle for supplementation given that a toxic dose of selenium from eggs would require consumption of more than 25 eggs per day over time, an unlikely situation. There is an option for simultaneous enrichment of eggs with several important nutrients, including omega-3 fatty acids, vitamin E, carotenoids (Surai and Sparks, 2001; Surai, 2002) and with a single egg it is possible to deliver around 50% of the human RDA for selenium. It appears that pork, beef and chicken meat, as well as milk, can also be enriched with selenium. In some areas with high selenium content in the feed (e.g. South Dakota) meat and milk produced are already naturally enriched with selenium (Lawler et al., 2004).

Before the advent of commercially available organic selenium for animal diets, the main problem in relation to the enrichment of eggs with selenium was the low efficiency of transfer of inorganic selenium (the selenite or selenate forms) to the egg. In fact, even high doses of selenite in the diet of laying hens were not able to substantially enrich eggs with this trace element (as reviewed by Surai, 2002). Indeed, replacement of sodium selenite by selenium-yeast in the chicken diet substantially increased selenium accumulation in eggs (Surai, 2000a; Paton et al., 2002; Payne et al., 2005; Pappas et al., 2005, 2006a, 2006b; Skrivan et al., 2008), improved their antioxidant defences (Surai, 2000; Pappas et al., 2006a; 2006b), and increased selenium concentration in muscles and other tissues (Pan et al., 2007; Payne and Southern, 2005). Similar effect of selenium-yeast was observed with quail (Surai et al., 2006).

Table 1. Some characteristics of food choice for selenium-enrichment (adapted from Yaroshenko et al., 2003).

The food should be:	Comments
A part of the population's traditional meals	It would be counter-productive to attempt a change in culturally based food habits by introducing a new type of food. Emphasis should be given to the possibilities of changing the composition of existing foods such as by selenium enrichment.
Consumed regularly in moderate amounts	Since the objective is to deliver the amount of selenium needed to meet RDA, it is necessary to choose food that is consumed regularly in moderate amounts. Over-supplementation is unnecessary and undesirable.
Consumed by the majority of the population	This is particularly important given that immune function is more likely to be compromised in groups such as children and the elderly.
Affordable	Affordability of food would play an important role in consumer choice.
Enriched with other health-promoting nutrients that are in short supply in the same population	Examples of nutrients critical to health that are frequently deficient include iron and iodine. Vitamin E and lutein are also in short supply in the human diet. This can greatly improve diets.
Supplying a meaningful amount of the nutrient (e.g. at least 50% RDA)	This is an important point that distinguishes true functional foods from products that include 'tag-dressing' amounts of nutrients for advertising purposes.

The concept of producing selenium-enriched eggs first originated at the Scottish Agricultural College in 1998 (Surai, 2000). Indeed, a wide introduction of organic selenium in the form of selenium-enriched yeast into poultry diets was a revolutionary decision, making it possible to produce eggs with an increased selenium concentration. Since the main form of selenium in the egg is Se–Met and chickens cannot synthesise this amino acid, inclusion of sodium selenite into the chicken diet has limited ability to produce enriched eggs. However, Se–Met from selenium-yeast is effectively transferred to egg yolks and albumin, providing the opportunity to produce selenium-eggs.

At the same time as these developments, many media channels around the world have taken the first step in promotion of the commercial production of selenium-enriched eggs (Table 2). It was later proved that the consumption of such eggs could provide a good source of selenium for man (Surai et al., 2004) and may provide a solution for global selenium deficiencies in man.

Selenium-enriched eggs in a global context

Today, selenium-enriched eggs are produced in more than 25 countries world wide, with the eastern European countries progressing the farthest in this respect. Russia is currently the most advanced country in this business, generating around 38 billion eggs, with 40% of poultry farms producing various modified eggs with increased levels of selenium, vitamins, PUFAs and other functional compounds (Fisinin, 2007). There are more than 20 poultry businesses in Russia producing selenium-eggs commercially. They are situated in various regions of the country ranging from St. Petersburg to Siberia and the Far East. Generally they are not competing with each other in the local markets. In most instances, these eggs are sold with distinguishable names and brands including 'Rejuvenating', 'Aksais's Sun', 'Spring of Cheerfulness', 'Universal', 'Cossack Village Eggs', 'Oval Wonder', 'Strong eggs', 'Activita', 'Selena', and 'Healthy Selenium' (Table 3).

The level of selenium delivered in a single Russian enriched egg varies from 20 μg to 35 μg. In many cases eggs are simultaneously enriched with vitamin E, however, as a rule, the amount of vitamin E delivered from a single egg is < 30% RDA. Prices for selenium-enriched eggs vary and are usually higher by 10–50% in comparison to normal

Table 2. Media output related to the super egg development (adapted from Surai, 2002).

Title	Newspaper	Date
Super egg that could poach the vitamin pill market	Daily Mail	June 12, 1998
Science goes to work on an egg	The Herald	June 12, 1998
Super egg	Cambridge Evening News	June 12, 1998
Good health is no yolk	The Express	June 12, 1998
Scientists go to work on creating 'super-egg'	The Times	June 12, 1998
Experts crack the super egg's secret	The Express	August 2, 1998
Scientists develop a natural panacea: new super egg bid to allay killer diseases	The Herald	April 5, 1999
Scientists go to work on a super-egg	The Guardian	April 7, 1999
Scots to market 'life-saving' eggs	The Sunday Times	April 5, 1999
Super-eggs to help fight against cancer	Metro	April 7, 1999
Could SUPEREGG save your life?	The Express	April 8, 1999
The egg that goes to work on your health	Daily Mail	April 7, 1999
New enriched egg could bring health benefits	Farmers Guardian	April 9, 1999

Table 3. Some examples of selenium-enriched eggs produced in various countries.

Country	Brand name of selenium-eggs
Columbus	UK, Belgium, Netherlands and other countries
Origin	Northern Ireland
Mega-Eggs	Ireland
NutriPlus	Malaysia
LTK Omega Plus	Malaysia
Selenium Plus	Malaysia
TPC Egg with Organic Selenium	Malaysia
Selen Egg	Thailand
Doctor Hen Egg	Thailand
Bounty Eggs	Philippines
Organic Selenium-Egg	Singapore
Bon Egg	Columbia
Mr Egg	Mexico
Heart Beat eggs	New Zealand
Tavas Yumurta	Turkey
Seker Yumurta	Turkey
Selenyum eggs	Turkey
NutriPlus	Portugal
Omega Pluss	Hungary
Vi Omega-3	Greece
Splepacich Vajec Eggs	Slovakia
Bag of Life (Koshik zhitja)	Ukraine
Spring of Life (Dzherelo zhitja)	Ukraine
Rejuvenating (Molodiljnije)	Russia
Aksais' sun (Aksaiskoye solnishko)	Russia
Spring of cheerfulness (Rodnik bodrosti)	Russia
Cheerful egg (Bodroe)	Russia
Universal (vSELENskoye)	Russia
Cossack Village Egg (Stanichnije)	Russia
Beautiful hen (Chochlatka)	Russia
Aktivita	Russia
Dr. Selenium	Russia
Oval Wonder	Russia
Mettlesome eggs (Molodetskoye)	Belarus

'table' eggs. The level of production of selenium-eggs as a percentage of total egg production on these farms varies from 1% to 20%.

Much more advanced selenium-egg production has been developed by Langut Ukraine, a company located in the Kiev region. The egg under the brand name of 'Bag of Life' and the trademark 'Eggs from a good hen' are produced at the level of 1.2 million daily and are sold all over the Ukraine. In fact, all of the eggs which are produced by the company are selenium-enriched. A single egg delivers about 30–35 μg of selenium (50% RDA), about 15–20 mg vitamin E (100% RDA) and is also enriched with natural carotenoids.

It is interesting to note that practically all of the aforementioned selenium-eggs are produced using selenium-yeast in the commercial form of Sel-Plex (Alltech Inc, USA) as a major source of selenium for laying hens at the level of 0.3–0.5 mg/kg in feed. One important advantage for Russia and the Ukraine in terms of selenium-egg production is that they do not need to comply with EU feed-additive legislation for local use, but they must follow their local regulations and they also have strong marketing support.

Safety of selenium-enriched eggs

Selenium-enriched eggs, as a rule, contain up to 30 μg of selenium per egg. Since the maximum safe dietary selenium intake (average NOAEL – 'no observed adverse effect level') is 819 μg (Whanger, 2004), to have any detrimental effect from selenium overdose one must consume more than 25 eggs a day for a long period of time. If we take into account the maximum safe dietary intake of selenium as identified by the Food and Nutrition Board (2000) to be 400 μg, one can consume 13 eggs a day for a long period of time, a situation difficult to imagine in practice. In most European and other developed countries, egg consumption is less than one per day, so the safety margin here is more than 10-fold.

Observations with selenium-egg production in various countries indicate the following (Surai, 2006):

1. Costs involved in selenium-egg production do not normally exceed 2% of the total feed costs.
2. Organic selenium supplementation of laying hens is associated with increased egg production, better shell quality, internal egg quality (Hough Units) and an improved Feed Conversion Rate (FCR). These

parameters pay money back and produce a profit at the level of 1:3–5. Therefore producing marketing for 'selenium-enriched' products is usually free of charge and can be used as an effective tool for promotion.

3. Additional inclusion of selenium to already existing modified eggs (omega-3, vitamin E-enriched, iodine-enriched, etc) can further enhance their quality and marketing potential without substantially increasing the price.
4. Labelling regulations differ substantially from country to country; however, a two-fold increase in selenium content of the egg would fit the 'selenium-enriched' category of most countries.
5. Some countries (e.g. in eastern Europe and Asia) allow claims for the health benefit of selenium, but in most areas it is only possible to include the level of selenium on the label and give a comparison to the RDA. Even such limited labelling would be a great advantage for producers.

The prospects for increased production of selenium-eggs worldwide are great and a major limitation in selenium-egg production is a lack of public knowledge concerning the beneficial effects of selenium in relation to human health. Indeed, the companies producing selenium-eggs should invest more into public education to increase the market for their product.

It seems that the selenium form expressed in eggs is highly nutritionally available. A recent clinical trial conducted in the Ukraine showed that consumption of two selenium-enriched eggs per day for eight weeks significantly increased the selenium level of the plasma of volunteers (Surai et al., 2004). Eggs consumed in the control group contained 7–9 μg Se/egg and test-group eggs were enriched with selenium in the range of 28–32 μg Se/egg. Blood was collected at the beginning and the end of experimental period and selenium was determined in plasma by hydride-generation atomic-absorption spectrometry with fluorometric detection. The level of selenium in the plasma of the volunteers living in the Kiev area of the Ukraine (0.055–0.081 μg/mL) was on the low side of the normal physiological range and was lower than reported in previous studies conducted with volunteers in Scotland (Surai et al., 2000). Consumption of commercially available eggs for eight weeks only slightly increased selenium in plasma, which reached physiological level (0.075–0.085 μg/mL). Consumption of two enriched eggs daily, which delivered the daily requirement of 55–65 μg selenium, for eight weeks, was associated with a significant increase in selenium concentration in the plasma. Plasma selenium reached 0.09–0.14 μg/mL, indicating improving selenium status of volunteers (Surai et al., 2004).

This is the first clinical trial proving that selenium-enriched eggs can be used to improve selenium status in countries with low selenium consumption, such as Scotland or the Ukraine. Selenium availability from eggs for human supplementation needs further elucidation and the effects of different dietary sources of selenium on plasma concentration probably depends on the initial selenium status of the individual. This study was very important for the Ukraine region, as selenium deficiency has been documented in people working in the Chernobyl area (Tutelian *et al.*, 2002; Golubkina *et al.*, 2002). Selenium and other antioxidants can be especially beneficial for people living in radionuclide-contaminated areas of the Ukraine.

In the UK, the only designer eggs available through the major supermarkets are the 'Columbus' brand produced by the Belgium company Belovo. These eggs, enriched in n3 fatty acids and vitamin E, first appeared in Belgium in 1997. Since then they have been sold in the UK (1998), Netherlands (1999) and India, Japan and South Africa (2000). Current production of the Columbus egg exceeds 50 million per year in Europe. To satisfy consumer demand in the UK, free-range Columbus eggs enriched with n-3 PUFAs, vitamin E and selenium are also on the supermarket shelves. These eggs are characterised by a balanced nutritional lipid composition (C18, n-6:n-3 = 1:1) and a favourable structural lipid ratio (long-chain PUFA, n-6:n-3 = 1:3).

Selenium-enriched meat

Various types of meat are important natural sources of selenium in human nutrition. For example, in 2003 world pig-meat production reached 95.8 million metric tons, while poultry meat rose to 75.2 million tons and the beef to 61.9 million tons (Best, 2004). In particular in 2000, an estimated £56 billion was spent on household food in the UK (Buttriss, 2002). In general, meat is a good source of selenium. However, selenium concentration in the meat varies substantially depending on geographical origin of the country and the selenium supplements used. For example, pork produced in the UK, Australia and the USA contains selenium at the levels of 14, 9.4–20.5 and 14.4–45.0 μg/100g, respectively (McNaughton and Marks, 2002). In Sweden, pork contained selenium at the level of 11.3 μg/100g (Daun et al., 2001). Indeed, it is well established that selenite or selenate dietary supplementation is not effective in increasing selenium concentration in the meat. The main form of selenium in muscles of animals fed on grain-based diet is Se–Met. For example, the selenium amino acids accounted for 91% (± 8%) of the total selenium (mean of 95 samples of seven tissues analysed over a period of 18 months; Bierla et al., 2008) with Se–Met comprising more than 60% of total selenium. When high doses of selenium-yeast supplementation were used, > 95% of the selenium in chicken breast and leg muscles was found in the form of Se–Met. It is known that animals cannot produce Se–Met, it must come with the food. This means that only organic selenium, in the form of Se–Met in the chicken, pig or cattle diet, can substantially increase the selenium concentration in the meat.

At high organic selenium supplementation, the selenium content in the loins of grower pigs was more than twice that of a comparison selenite group (Mahan, 1999). For example, adding selenite to the pig diet at the level of 0.5 mg/kg increased selenium concentration in loin from 0.114 mg/kg to 0.189 mg/kg, while adding selenium-yeast into the pig diet in the same amount increased selenium levels up to 0.362 mg/kg (Mahan and Parrett, 1996). Therefore 100 g of such pork could provide about 66% RDA in selenium. The opportunity of producing selenium-enriched pork is clearly shown by Kim and Mahan (2001) who studied comparative effects of high dietary levels of organic and inorganic selenium on selenium content in tissues of growing–finishing pigs. In fact, dietary supplementation with organic selenium at the level of 5 mg/kg for 12 weeks caused the selenium concentration in loin to be increased from 0.154 mg/kg to up to 3.375 mg/kg. This extremely high selenium dose caused only a slight decrease (by 2.5%) in body weight without changing feed intake (Kim and Mahan, 2001), indicating comparatively low toxicity and commercial opportunities in using organic selenium in high doses to produce selenium-enriched pork. Indeed, selenium-enriched pork can be sold separately or can be included in various meat-based products to enhance their selenium content. These data were a background for the development of a technology of pork enrichment with selenium, and this food is already on the market in Korea. It is interesting that in addition to increased selenium level in the meat, there are other important improvements in pork quality (Cole, 2000).

These are:

- Tender and chewy
- Good colour
- Low fat
- Low drip loss
- Reduced pig odour

Selenium pork is served in special restaurants where the information about benefits of selenium is widely available to educate customers and to increase the demand for this functional meat. Selenium pork is also commercially available in Canada.

Beef is considered to be a major source of dietary selenium, but the concentration of selenium in edible beef products is very variable and depends on its geographical origin (Finley *et al.,* 1999). For example, in the review of McNaughton and Marks (2002), selenium concentration in beef was reported to be 3.0–7.6 μg/100g, 2.2–8.3 μg/100g, 7.2–12.1 μg/100g and 13.4–19.0 μg/100g in the UK, New Zealand, Australia and the USA, respectively. In North Dakota, the selenium concentration in beef was 27, 38, 40, 47 and 67 μg/100g in the south-east, central, south-west, south central and north-west, respectively (Hintze et al., 2001). Taking into account that average red meat consumption in the USA was 57 kg/year, Finley *et al.* (1999) calculated that daily intakes of selenium from beef in various USA areas would range from 40 μg/day up to 100 μg/day. Selenium in beef raised in North Dakota could reach the fairly high levels of 67 μg/100 g (Finley et al., 1996; Hintze et al., 2001, 2002). The opportunity for the substantial enrichment of beef by selenium is demonstrated by an analysis of beef produced in a seleniferous area of South Dakota (Hintze et al., 2002). Indeed, selenium levels in ribeye, sirloin, clod and round were 1.20 μg/g, 1.19 μg/g, 1.21 μg/g and 1.22 μg/g, respectively. After 14 weeks on a high selenium diet (11.9 mg/kg from seleniferous wheat and hay) the selenium level in muscles further increased up to 2 μg/g (Hintze et al., 2002). Inclusion of such beef in any meat foods could substantially enrich it with selenium. It is also interesting to note that, in the study, high selenium intake for 14 weeks of the experimental period did not affect feed intake, average daily gain and final weight of steers.

In European and some Asian countries, selenium concentration in beef is much lower than in the USA. However, it is possible to substantially increase the selenium content of beef by inclusion of organic selenium into the diet of cattle. For example, when Holstein bulls at the age of 22 months were supplemented with organic selenium in the form of selenium-yeast at the level of 4 mg/head/day for 30 days, selenium concentration in the longissimus dorsi muscle increased from 0.107 μg/g up to 0.223 μg/g (Simek et al., 2002). At the same time, enrichment of beef with selenium was associated with decreased drip loss and fluid loss during beef storage. Similarly, supplementing one-month-old calves with 0.3 mg/kg organic selenium in the form of selenium-yeast for two months increased the selenium concentration in striated muscle from 0.092 μg/g to up to 0.263 μg/g (Pavlata et al., 2001). Therefore 100 g of such selenium-enriched beef could provide about 40–50% of the RDA in selenium. Lamb meat can also be substantially enriched with selenium, and recently Bierla et al. (2008) showed that 100 g of selenium-lamb produced by feeding organic selenium can deliver about 50% RDA in selenium.

Selenium concentration in commercial chicken meat varies substantially. Inclusion of selenite in the chicken diet, even in high concentrations (up to 8 mg/kg), only moderately increased the selenium level (up to 23–26 μg/100 g) in chicken meat (Arnold et al., 1973). On the other hand, as in the case with pork and beef, there is the opportunity to increase the selenium content in chicken meat by the inclusion of organic selenium into the diet. For example, ‘Selen Chicken’ is a premium chicken brand, offering added value to producers and retailers. The development of this kind of meat started in Korea and is now under development in other countries. For example, under commercial conditions in the Ukraine, the RozDon Company produced chicken meat enriched with selenium and vitamin E by the dietary inclusion of organic selenium and increased doses (250–500 mg/kg) of vitamin E (Yaroshenko et al., 2004). The results indicated that the dietary inclusion of organic selenium from day old to slaughter significantly increases selenium level in the breast (from 85.2 ng/g to 284.3 ng/g) and leg muscle (from 72.2 ng/g to 274.2 ng/g) in comparison to the chickens that were fed a commercial diet supplemented with selenite. Increased dietary vitamin E (250–500 mg/kg) during the last four weeks of growth also significantly increased vitamin E concentration in muscle tissue. A combination of increased concentrations of selenium and vitamin E was responsible for substantial decreases in lipid peroxidation in the meat during storage at 4°C and at –20°C. In fact, the concentration of malondialdehyde in the experimental meat was significantly reduced as a result of the increased antioxidant concentrations in the meat. Data indicate that the consumption of approximately 100 g of selenium-enriched chicken meat, which can be produced commercially, could deliver about 50% of the RDA for selenium and could help in solving problems of selenium deficiency (Surai, 2006). Furthermore, the combination of increased selenium and vitamin E concentration in chicken meat could improve meat quality during storage. There is also the valuable option of producing selenium-turkey, where the growth period is substantially longer. Indeed, commercial turkey meat produced in the USA contains selenium at a level of 34 μg/100 g (Schubert et al., 1987), reflecting the high-selenium soils in the USA and demonstrating the possibility of increasing the selenium content of turkey in other regions by using organic selenium in the diet.

The bioavailability of selenium in meat from domestic animals has also been evaluated. In the experiment with rats, after nine weeks of dietary selenium repletion, it was shown that relative selenium availability (based on liver GSH-Px) was as follows: pork 86%, sodium selenite 81%, Se–Met 80%, beef 80%, chicken 77%, veal 77%, and lamb 58% (Wen et al., 1997). Similarly, it was shown that beef is a highly bioavailable source of dietary selenium when compared with selenite or selenomethionine (Shi and Spallholz, 1994). Employing similar tests, the authors found that after selenium depletion the recovery of liver GSH-Px activity compared to control animals (set at 100%) was: with selenite (98%), selenate (117%), raw beef (127%) and cooked ground beef (139%). The data suggests that the bioavailability of selenium from ground beef is greater than that from either selenite or selenate. Therefore meat as a source of selenium is characterised by high availability.

It is important to stress that the consumption of selenium-meat is a safe option, since in order to reach a level of 400 μg/day (the maximum safe dietary intake of selenium), one would have to consume more than 1 kg of meat every day, for a long period of time.

Optimal selenium forms in the diets for selenium-egg and selenium-meat production

Selenium transfer to the egg depends on many different factors: analytical techniques used for selenium analysis and the form of selenium in the diet could be important variables. For example, in experiments conducted in Croatia, it was shown that the provision of organic selenium in concentrations ranging from 0.3 mg/kg to 0.5 mg/kg in feed for hens tended to accumulate only 30% more selenium in the eggs when compared with the same concentrations of inorganic selenium (Valentic et al., 2003). These results contradict many other trials previously described, which showed that the selenium levels in eggs were twice as high when feed was supplemented with selenium-yeast, in comparison to inorganic forms of selenium. Therefore it seems likely that the effect of organic selenium on poultry depends on the preparations used; for example, in most of the studies related to selenium-enriched eggs and meat reported above, selenised yeast was fed in the form of Sel-Plex. However, other forms of organic selenium could give completely different results. A selenised yeast, produced in Poland under laboratory conditions, was included in the chicken diet for 11 days at 0.5 mg/kg and a comparison with the same amount of sodium selenite was made (Dobrzanski et al., 2003). There was no difference in selenium availability from both sources and the selenium concentration in the egg content increased only slightly, by 10.5%. Similarly, a selenium malt was produced in China under laboratory conditions. It was claimed to be organic selenium and was fed to laying hens at 0.51 mg/kg for 24 days and it did not show any advantage over sodium selenite, in terms of selenium content of the egg (Jiakui and Xialong, 2004). Furthermore, a study conducted in China reported no difference in selenium concentration in the muscle of chickens fed either sodium selenite or selenium yeast at 0.2 mg/kg (Wang and Xu, 2008). Another paper from China reported only marginal differences in selenium content in muscles of laying hens (0.182 mg/kg vs. 0.149 mg/kg) even after 1 mg/kg supplementation with selenium yeast, when compared to sodium selenite supplementation (Pan et al., 2007). When organic selenium in the form of Se–Met was used in the chicken diet at 0.3 mg/kg, there was no difference in the selenium content of the egg compared to those eggs laid by hens fed on the diet supplemented with sodium selenite (Chantiraticul et al., 2008). Indeed, it has been proven that the efficiency of transfer to the egg of sodium selenite from the diet is comparatively low (Surai, 2006). For example, even high dietary supplementation of the chicken diet with selenium in the form of sodium selenite (1 mg/kg) increased the selenium content in the egg by only 39% (Bargellini et al., 2008). Attempts at using pure Se–Met commercially could face problems with its stability and it seems likely that the products of oxidation of Se–Met could not be used by the body as an effective and available source of selenium (Surai, 2006). Furthermore, such products of oxidation could be potentially toxic.

It seems likely that the selenoamino acid composition of the yeast depends on various factors, including yeast species and growth conditions, as well as the analytical techniques used. For example, recently three different commercial yeast products were analysed. Results showed that the proportion of water-soluble selenium varied from 11.5% up to 28.0% and the water-insoluble polysaccharide-bound selenium proportion varied from 15.5% up to 72% (Encinar et al., 2003). This means that not all yeast products are the same and that results obtained in studies with one product cannot be generalised to all yeasts.

Conclusions

Selenium-eggs are perfectly suited to the category of functional foods. A single egg can deliver 50% of the RDA in selenium, and since most European countries are selenium-deficient (Surai, 2006), this could have additional benefits, beyond those provided by normal eggs. Eggs form an essential part of many different foods and dishes, and their quality could be enhanced beyond their nutritional value. Selenium-enriched eggs could also have a substantial effect on gastro-intestinal functions (one of the purposes of functional foods) providing selenium for the antioxidant enzyme GI-GSH-Px, which is responsible for the prevention of oxidised lipid absorption, and which may also offer protection against heart disease and cancer. Furthermore, selenium delivered in eggs could have a beneficial effect on the antioxidant/pro-oxidant balance in the intestine (Surai, 2006).

Regarding diversity in enriched poultry products, it is interesting to note that selenium-enriched quail eggs are already commonly seen on supermarket shelves in the Ukraine and Belarus. Selenium-enriched meat and milk production is a next step in widespread functional food production.

Decreased selenium levels in feeds and foods in many cases reflect the consequences of our agricultural practises. For example, the usage of inorganic fertilizers rich in sulphur interferes with selenium assimilation from soil, and soil acidification also decreases selenium availability. Therefore eggs produced by free-range poultry fed on natural feed sources grown on well-balanced soils 100–200 years ago would have contained much higher selenium concentrations than we currently see in eggs from many European and Asian countries. Recent observations (Pappas et al., 2006) indicated that the selenium levels in eggs from wild birds were substantially higher than in commercial hatching eggs. Selenium-enrichment of eggs, meat and milk may be viewed as merely production of naturally designed food ingredients. Indeed, production and commercialisation of such organic selenium sources as selenised yeast have already opened a new era in selenium supplementation of animals and has provided a real chance for producers to differentiate and add value to their poultry products and to meet the increasingly diverse requirements of consumers.

Selenium-eggs in many countries have successfully made their way from niche markets to mainstream food sales. Indeed, it is possible to provide consumers with a range of animal-derived products that have been nutritionally improved in such a way that they can deliver substantial amounts of health-promoting nutrients to improve the general diet and help to maintain health. Therefore, without changing eating habits and traditions of the various populations, it is possible to solve problems related to deficiency of various nutrients, in particular selenium. The consumer will go to the same supermarket to buy the same animal-derived products (eggs, milk and meat), and then cook and consume them as usual. The only difference will be in the amount of specific nutrients delivered with such products. A simple calculation indicates that, for example, in Europe, if one consumed all of one's meat and eggs as selenium-enriched products, it would still be difficult to reach 300 μg/day, the dose shown by Clark et al. (1996) study to be cancer protective.

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