

Selenium-enriched eggs as a source of selenium for human consumption

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Abstract: Hippocrates' observations on the relationship between health and food choices initiated discussions about the factors determining our health many centuries ago. However, during the last decade it has become obvious that while our lifestyle, including diet, stress, smoking, medical attention and exercise; and genetics are a major determinant of our health status, it is diet that plays the central role. The effect of nutrition on human health has received substantial attention, and the traditional medical view that diet and nutrients play only limited roles in human health is being revised. In most developed countries nutritional practice has changed the focus from combating nutrient deficiencies to addressing nutrient requirements for maintaining good health throughout life. Several recent reviews have discussed the role of selenium (Se) in human health and disease in detail, concluding that Se deficiency is a global problem that urgently needs solving. Analysing recent publications related to human health and poultry products, we deduced that Se-enriched eggs could be used to deliver this trace mineral to humans. In particular, development and commercialisation of the organic form of selenium opens a new era in the production of selenium-enriched products. Egg selenium content can be easily increased when organic selenium is included in the diet at a level to provide 0.4 ppm Se. As a result, the technology for the production of eggs delivering ~50% (30–35 µg) of selenium recommended daily allowance (RDA) has been developed and successfully tested. Currently companies all over the world market Se-enriched eggs including the UK, Ireland, Malaysia, Thailand, Australia, Turkey and the US. Prices for those eggs vary from country to country and are similar to those for free-range eggs. The scientific, technological and other advantages and limitations of the designer/modified eggs as a functional food are discussed in this paper.

Keywords: selenium, functional food, eggs, human

Introduction

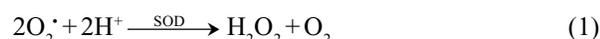
Relationships between diet and human health have received substantial attention in the last few years with the realisation that unbalanced diets can cause serious health-related problems. The natural antioxidants are considered particularly important. It is well known that free radicals produced under both normal and abnormal physiological conditions can have damaging effects on polyunsaturated fatty acids (PUFA), DNA and proteins. Antioxidant protection is vital for either prevention or substantial reduction of the damage caused by free radicals and products of their metabolism. Our food provides a major part of natural antioxidants including vitamin E, carotenoids, flavonoids and selenium. Particular interest in selenium was 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 twofold. Additionally, there are data indicating that inadequate selenium consumption is associated with poor health and development of various viral

and bacterial diseases. Unfortunately, in many countries all over the world human food ingredients do not provide sufficient selenium. As a result, finding solutions to this public health problem are on the agenda of many government bodies. Since selenium in high doses is toxic, it is necessary to make sure that the supplemental level of this trace element does not exceed physiologically required amounts. Results of various research studies conducted over the last five years indicate that enrichment of animal-derived food products with selenium through the special supplementation of food animal diets could be an effective way of increasing human selenium status in countries where selenium consumption falls below the recommended daily allowance (RDA). For example, selenium consumption in the UK is shown to be about 50% of the RDA.

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Antioxidant systems in the human body

Since free radicals are produced under physiological conditions, the evolutionary development of cellular and tissue antioxidant systems is critical to survival in an oxygenated atmosphere (Halliwell and Gutteridge 1999). There are three major levels of antioxidant defence in the cell (Surai 2002). The first level of defence is based on a family of antioxidant enzymes called superoxide dismutases (SOD) that together are responsible for dismutation (detoxification) of the superoxide radical, which is the major radical produced in biological systems. This reaction can be summarised as follows (reaction 1):



Since hydrogen peroxide (H_2O_2) formed in this reaction is still toxic and, in the presence of transition metals (eg Fe or Cu), can generate more powerful free radicals (eg OH^{\cdot}), another family of antioxidant enzymes called glutathione peroxidases (GSH-Px) also belong to the first level of antioxidant defence. These enzymes are responsible for conversion of H_2O_2 into water (reaction 2):



Similarly, H_2O_2 can be reduced to water by catalase. Recently it has been shown that thioredoxin peroxidases are also capable of directly reducing hydrogen peroxide (Nordberg and Arner 2001). Therefore these two enzymes also belong to the first level of antioxidant defence. Since transition metals must be bound to proteins to prevent their participation in free radical generation, metal-binding proteins can be included in the same first level of antioxidant defence.

The first level of antioxidant defence cannot completely prevent free radical formation. It is the second level of antioxidant defence that is responsible for restriction and prevention of chain reactions of lipid peroxidation by scavenging free radicals. Such chain-breaking antioxidants as vitamin E, vitamin A, carotenoids, ascorbic acid, ubiquinol, uric acid and so on form this important part of antioxidant defence. In recent years it has become obvious that antioxidant recycling is the major mechanism providing high efficiency of antioxidant defence. Therefore, vitamin E recycling by means of ascorbic acid, reduced glutathione, ubiquinol, carotenoids or other antioxidants (Surai 2002) is a key element to maintaining effective protection in various tissues preventing the damaging effects of free radicals and toxic products of their metabolism.

Table 1 Glutathione peroxidase characteristics

	<i>Localisation</i>	<i>Subunit size (kDa)</i>	<i>Se</i>	<i>Substrates</i>	<i>Electron donors</i>	<i>Other characteristics</i>
Cytosolic GSH-Px	Intracellular, cytosolic, partly mitochondria	21.9	+	H_2O_2 , t-BHP	GSH	Erythrocytes, kidney and liver
Gastrointestinal GSH-Px	Intracellular, cytosolic	21.9	+	H_2O_2 , t-BHP	GSH	Mucosal epithelial cells in GIT
Extracellular (plasma) GSH-Px	Plasma	25.5	+	H_2O_2 , t-BHP, phospholipid hydroperoxides	GSH, thioredoxin, glutaredoxin	Expressed in kidney
Phospholipid hydroperoxide GSH-Px	Intracellular, partly cytosolic, partly mitochondrial, partly membrane-bound	22.1	+	H_2O_2 , phospholipid hydroperoxides	GSH, DTT, 2-ME, L-Cys	Renal epithelial cells and testes
Sperm nuclei GSH-Px	Intracellular, partly cytosolic, partly mitochondrial, partly membrane-bound	34.0	+	H_2O_2 , phospholipid hydroperoxides	GSH	Testes, late spermatids
Epididymal GSH-Px	Epididymal fluid, epididymis	25.2	–	Low activity towards H_2O_2 and organic hydroperoxides	GSH	Caput epididymis
Non-selenium GSH-Px		25.0	–	H_2O_2 , organic hydroperoxides, phospholipid hydroperoxides	GSH	Bovine ciliary body, rat olfactory mucosa, human and mouse liver

Source: Adapted from Hayes and McLellan (1999); Singh and Shichi (1998); Schwaab et al (1998); Pfeifer et al (2001). Abbreviations: t-BHP: tert-butylhydroperoxide; DTT: 1,4-dithiothreitol; 2-ME: 2-mercaptoethanol; L-Cys: L-cysteine.

Even the second level of antioxidant defence is not able to detoxify all free radicals, and as a result the damaged PUFAs, DNA and proteins should be repaired or removed from the cell. The third level of antioxidant defence is based on the specific enzymatic systems responsible for removal/repair of the damaged biological molecules. For example, damaged protein degradation in the proteasomes could be considered an important mechanism of antioxidant defence.

Selenoproteins as an integral part of the antioxidant system

It is generally accepted that in biological systems selenium participates in various physiological functions as an integral part of a range of selenoproteins. The selenoprotein family includes at least 20 eukaryotic proteins (Kohrle et al 2000) and about 35 selenium (Se)-containing proteins or protein subunits that can be distinguished by two-dimensional electrophoresis after *in vivo* labelling with ⁷⁵Se (Behne et al 2000). It is interesting to note that expression of individual eukaryotic selenoproteins is characterised by high tissue specificity; depends on Se availability; can be regulated by hormones and; if compromised, contributes to various pathological conditions (Kohrle et al 2000). Glutathione peroxidase (GSH-Px) and thioredoxin reductase (TR) are the most abundant antioxidant Se-containing proteins in mammals (Gladyshev et al 1998). Major characteristics of GSH-Px are shown in Table 1.

There are tissue and species specificities in the expression of various selenoproteins. In general, different forms of GSH-Px perform their protective functions in concert with each enzyme providing antioxidant protection at different sites of the body. For example, gastrointestinal (GI) GSH-Px could be considered a barrier against hydroperoxide resorption (Brigelius-Flohe 1999). Furthermore, in the gastrointestinal tract there are at least three more selenoproteins including plasma GSH-Px, selenoprotein P and thioredoxin reductase (Mork et al 1998). Plasma GSH-Px is an important antioxidant in plasma, which together with selenoprotein P and other antioxidant compounds maintains antioxidant protection. On the other hand, phospholipid hydroperoxide (PH) GSH-Px is an important antioxidant inside biological membranes where lipid peroxidation occurs and lipid hydroperoxides are produced.

Removal of hydrogen peroxide is not the only function of GSH-Px. In fact, maintenance of cellular redox state is another important function of these enzymes; and GSH-Px are involved in physiological events such as differentiation,

signal transduction and regulation of pro-inflammatory cytokine production (Ursini 2000). Peroxynitrite scavenging by GSH-Px (Sies et al 1997) could also play a prominent role in cell signal transduction events. Participation of GSH-Px enzymes in regulating biosynthesis of leukotrienes, thromboxanes and prostaglandins is responsible for the modulation of inflammatory reactions, whereas PH-GSH-Px can bring about cytokine-induced transcriptional gene activation (for review see Kohrle et al 2000).

Therefore, it is clear that selenoproteins are involved in the regulation of a range of physiologically-important processes that include antioxidant defence and intracellular redox status, and consequently influence the expression of various genes and immunocompetence.

Selenium deficiency and its consequences for human health

Selenium is a key component of a number of functional selenoproteins required for normal health. Selenium concentration in various foods varies substantially, with Brazil nuts containing the highest Se concentration (Table 2). For example, in the UK the main contributors to the Se daily consumption are meat and meat products (32%), dairy products and eggs (22%), bread and cereals (22%) and fish (13%) (Table 3). Selenium enters the food chain through incorporation into vegetable proteins as the amino acids selenomethionine and selenocysteine. The British government's defined reference nutrient intake is 75 µg/day for men and 60 µg/day for women (Rayman 2000). USA

Table 2 Selenium concentrations in various European food sources

<i>Food</i>	<i>Selenium content (µg/100 g fresh weight)</i>
Eggs	19.4 ^a
Beef	7.6
Pork	14.0
Lamb	3.8
Poultry	18.5 ^a
Fish	36.0 ^a
Liver	42.0
Kidney	145.0
Milk	1.5
Dairy produce	3.2 ^a
Bread	4.5
Cereals	11.0
Fruit	1.0
Vegetables	2.0
Brazil nuts	254.0

Source: Adapted from Brown and Arthur (2001).
^a BNF (2001).

Table 3 Estimated intake of Se from different food in the UK in 1997

Food	% of total intake
Meat and meat products	32
Dairy products and eggs	22
Bread and cereals	22
Fish	13
Vegetables	6
Other foods	5

Source: Adapted from BNF (2001).

RDAs for selenium are very similar at 70 and 55 µg/day for men and women, respectively (NRC 1989). The recently revised US RDA is 55 µg/day for both men and women (Combs 2001). An intake of 40 µg/day was suggested as the minimum selenium amount required for humans (Whanger 1998). A great body of evidence indicates that European intakes of selenium are falling (Rayman 2000). In particular, it is the case in the UK (Table 4). For example, in 1978 selenium intake in Britain was 60 µg/day, seven years later it was only 43 µg/day and in 1990 it fell to 30 µg/day. Even in 1997, the average reported selenium intake was only 43 µg/d (Shortt et al 1997). Dietary intakes of selenium in other countries vary considerably, but in many countries intake is still lower than the RDA. Countries with known selenium intakes below RDA include Egypt (29 µg/day), Belgium (30 µg/day), Turkey (32 µg/day), Sweden (38 µg/day), Slovak Republic (38.2 µg/day), France and Germany (47 µg/day), and Italy (49 µg/day) (Reilly 1996; Kadrabova et al 1998). There are also specific categories of people, for example vegans, whose diet does not provide a sufficient amount of selenium (Larsson and Johansson 2002).

The decline in selenium intake is reflected in decreased serum and whole blood selenium concentrations (Alfthan and Neve 1996; MacPherson and Barclay 1997). The low selenium concentration in the blood is associated with increased risks of spontaneous abortions in women

Table 4 Estimated selenium intake in the UK

Year	Se intake (µg/day)	Reference
1974	60	(BNF 2001; Church 2000)
1978	60	(Thorn et al 1978)
1985	63	(Church 2000)
1990	30	(MacPherson et al 1993)
1994	34	(Barclay et al 1995)
1995	29–39	(BNF 2001; Church 2000)
1997	29–51	(BNF 2001; Shortt et al 1997) (MAFF 1997, 1999)
2000	39	(Ysart et al 2000)

(Barrington et al 1996) and male subfertility (Bleau et al 1984). Particularly in humans, seleno-dependent enzyme PH-GSH-Px appears to be indispensable for structural integrity of spermatozoa, sperm motility and viability (Foresta et al 2002). Decreased Se concentration in blood is also associated with increased risk of cancer (Clark et al 1984; Willett et al 1983) and cancer mortality rates (Clark et al 1991; Schrauzer et al 1977; Yu et al 1985). An inverse relationship between blood Se concentration and cardiovascular disease has also been reported (Kok et al 1989). Epidemiological studies indicate an association between low dietary selenium status and increased risks of cardiomyopathy, cardiovascular disease and carcinogenesis in various sites of the body (Badmaev et al 1996). Several studies have suggested that selenium deficiency may be associated with an increased risk of coronary heart disease (CHD). In a recent study in a rural coastal community in Japan the atherogenic index was found to be significantly higher in the low selenium intake group than in the middle and high selenium intake groups in males. Further, dietary intake of non-fish Se had a positive correlation with HDL cholesterol and an inverse correlation with the atherogenic index in all subjects (Miyazaki et al 2002).

There are some indications that selenium can regulate inflammatory mediators in asthma. For example, the UK intake of selenium was negatively ($P=0.002$) associated with asthma (Shaheen et al 2001). In a double blind multi-centric placebo-controlled study the effects of selenium supplementation (200 µg/day) in rheumatoid arthritis was investigated, and when examining the quality of life a significant ($P<0.01$) improvement in arm movements and health was evidenced in selenium-treated patients (Peretz et al 2001).

Selenium supplementation of the human diet (200 µg daily for 4.5 years) was associated with a significant (by 50%) decrease in cancer mortality (Clark et al 1996). The selenium-treated group had substantial reductions in the incidence of prostate cancer, total cancer incidence and mortality (Clark et al 1998). Of all recent human cancer intervention studies, that selenium trial was the most successful (Ip 1998). Selenium has been shown to have other health-related benefits. It is required for sperm motility and may reduce the risk of miscarriage (Rayman 2000). The administration of selenium to sub-fertile patients (100 µg per day) significantly increased sperm motility and chance of successful conception (Scott et al 1998). Selenium has a protective effect against age-related immunosuppression (Turner and Francis 1991). Dietary selenium supplementen-

tation increased the humoral response after vaccination and could have considerable public health importance by reducing morbidity from respiratory tract infections in elderly patients (Girodon et al 1999).

The possibility that a subclinical deficiency of selenium might exist in a sample of the British population was examined by giving a selenium supplement for five weeks (Benton and Cook 1990). Using a double-blind crossover design, 50 subjects received either a placebo or 100 µg selenium on a daily basis. On three occasions they filled out a profile of moods questionnaire. Mood did not change when taking the placebo, whereas subjects receiving selenium reported a substantial improvement after both 2.5 and 5 weeks. The lower the initial level of selenium in the diet the more reports of a decrease in anxiety, depression, and tiredness following 5 weeks of selenium therapy (Benton and Cook 1991). More recent results suggest that persons with low selenium status might experience relatively depressed moods and supports the idea that selenium has a special role in the regulation of brain metabolism and function (Hawkes and Hornbostel 1996).

Reilly (1998) listed more than 40 human diseases and conditions associated with selenium deficiency. These included ageing, arthritis, cancer, cardiovascular disease, cataracts, cholestasis, cystic fibrosis, diabetes, immunodeficiency, Kaschin-Beck disease, Keshan disease, lymphoblastic anemia, macular degeneration, muscular dystrophy, stroke and others. Adequate selenium is also essential for immune function and can protect the immune system from oxidative damage (McKenzie et al 1998). In particular, while deficiency has an adverse effect on immunocompetence, selenium supplementation appears to enhance the immune response (Rayman 2002). These studies clearly indicate that selenium plays an important role in human health and disease prevention. The mechanisms of selenium participation in such conditions need further elucidation, but it appears that in many cases the antioxidant role of selenoproteins is the driving force.

Since selenium content in plant-based food depends on its availability from soil, the level of this element in human (or food animal) foods varies among regions. There are several potential options when considering ways to improve human selenium intake. These include direct supplementation, soil fertilisation, supplementation of food staples such as flour and the production of functional foods.

In some countries organic selenium supplements in tablet form are available to health-conscious consumers. Many prominent scientists have championed the use of such

natural antioxidants. For example, the late Professor Pauling (a Nobel Prize winner) consumed 10 g of vitamin C per day without any obvious adverse effects (Weisburger 1997). Another example is Professor Shrauzer, known for his pioneering work related to the medical application of organic selenium, who regularly consumes selenium supplements. There are similar examples for vitamin E and carotenoid consumption as dietary supplements. However, there are many people who do not like swallowing capsules, cannot afford them or are simply unaware of the need to increase daily selenium intake.

Soil selenium availability is dependent on both selenium content and soil pH. In areas where soil selenium content is low (Northern Europe, New Zealand) sodium selenate is added to fertilisers (Alfthan 1993; Oldfield 1999). This approach has been successful in Finland and New Zealand, but has had limited interest in other countries because of environmental issues. Much more common is low crop selenium content owing to low soil pH. Plants cannot take up selenium when pH is below 7, therefore food crops grown on these soils have low selenium content.

Supplementation of staple foods such as bread flour is another approach to improving selenium status of the human population (Rayman 1997). Alternatively, selenium-enriched yeast may be used to produce bread (Rumi et al 1994). This approach deserves close consideration owing to its practical ability to reach wide segments of the population and previous success with other trace element deficiencies such as iron. For example, in China Se-enriched wheat flour is produced by its fortification with a Se-enriched mushroom extract (Combs 2000).

A fourth strategy is the production of 'functional foods' enriched with selenium (Surai 2000).

Selenium-enriched products

Several important factors must be considered when choosing the best food supplementation strategy for a given population. Such factors are shown in Table 5.

Among food animal products, the egg is ideally suited to meet this list of requirements. The egg 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 30 eggs per day over time, an impossible situation to imagine. There is an option of simultaneous enrichment of eggs with several important nutrients, including omega-3 fatty acids, vitamin E, carotenoids (Surai

Table 5 Some characteristics of food choice for Se-enrichment

<i>The food should be</i>	<i>Comments</i>
A part of traditional meals for the population	It would be counterproductive 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 eg, by selenium enrichment.
Consumed regularly in a moderate amount	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 the consumer choice.
Enriched with other health-promoting nutrients that are in short supply in the same population	Examples of minerals 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 give a greater improvement in the diet.
Supplying a meaningful amount of the nutrient (eg 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.

and Sparks 2001; Surai 2002), and with a single egg it is possible to deliver at least 50% of the RDA for selenium.

Improving the image of the egg

The main problem with the consumption of eggs is that the image of the egg in the mind of the consumer is not necessarily always good. Despite the nutritious qualities of the egg, its comparatively high content of cholesterol has been a driving factor in declining egg consumption for the last 20 years. The problem started when cholesterol was implicated as an important risk factor of coronary heart disease (CHD), the leading cause of death in developed countries. The direct relationship between the levels of plasma cholesterol and atherosclerosis was experimentally demonstrated in an animal model (rabbits) 89 years ago (Anitschkow and Chalataw 1913). Since that time numerous studies have been devoted to the subject. In particular, a consistent correlation was found between levels of total cholesterol and CHD in populations living in different countries (Keys 1980). Therefore, dietary cholesterol became the centre of attention because of its association with heart vascular disease development. That information provided the stimulus for mass media blaming cholesterol for many pathological conditions in the human body. As a result, many dieticians and doctors started to recommend lower egg consumption to avoid excess cholesterol in the diet.

Similarly, it was initially believed that egg consumption was associated with a rise in blood cholesterol (Yaffee et al 1991) and, as a consequence, was deleterious to health and life expectancy. The situation deteriorated when problems with egg contamination with *Salmonella* were reported

publicly. In the wake of health fears, whole egg consumption in Britain has fallen by almost half in the past five years, from more than three eggs a week to 1.70 eggs. Similar decreases in egg consumption have been reported in other countries, including the US (Stadelman 1999; Lewis et al 2000). The proliferation of magazine articles and public statements by organisations such as the American Heart Association relating eggs to blood cholesterol and heart disease caused a downward trend in egg consumption (McIntosh 2000).

However, our understanding of cholesterol metabolism has substantially improved since the initial furore over cholesterol, food animal products and heart disease. Knowledge of reverse cholesterol transport by HDL from the vessel wall to the liver for the catabolism (Lacko and Pritchard 1990) was an important milestone changing the current views of cholesterol intake. Dietary cholesterol is not regarded anymore as the major determinant of cholesterol levels in the blood. There are other more important determinants of this parameter such as saturated fat intake. More is also known about the development of coronary heart disease (Shaper 1987). In addition, more detailed analyses of many cholesterol-lowering trials showed that a decreased coronary morbidity did not reflect changes in total mortality (Libbi et al 2000), which was not changed. Furthermore, after analysing results from 27 studies involving 30 902 person-years of observation, Hooper et al (2001) concluded that alterations of dietary fat intake had a positive effect on cardiovascular events but practically no effect on total mortality.

Correlations drawn between nutrient intake and longevity in the Japanese since World War II illustrate this

point. It was found that sufficient intakes of animal protein and fat are crucial for attaining longevity (Shibata 2001). It is interesting that low serum cholesterol was deleterious for higher levels of functional capacity and accelerated depressive status in the elderly in the community. High intakes of milk and fats and oils had favourable effects on 10-year (1976–1986) survivorship in 422 urban residents aged 69–71 (Shibata et al 1992). The survivors revealed a longitudinal increase in intakes of animal foods such as eggs, milk, fish and meat over the 10 years. Furthermore, an increase in total cancer mortality in lung, prostate and colon was observed in men >60 years of age with low plasma cholesterol in Switzerland (Eichholzer et al 2000).

Results of many recent studies have shown that large numbers of eggs can be consumed over lengthy periods without adverse changes to plasma cholesterol or other lipid components. Furthermore, it is a general misconception that elevated plasma cholesterol represents the main atherogenic stimulus. It seems likely that the time has come to reconsider the egg's image and to distinguish between scientific fact and conjecture.

Ginsberg et al (1994) showed that consuming two eggs per day did not change serum cholesterol; and consumption of four eggs per day had only a slight effect on this parameter. Similarly, consumption of up to 14 eggs per week by students did not alter serum cholesterol levels (Vorster et al 1992). Analyses of the results from over 30 years of more than 2750 patients indicated that for the majority of individuals modest changes in dietary cholesterol have little if any effect on plasma lipoprotein cholesterol level (McNamara 1995). McNamara also calculated that a reduction in dietary cholesterol intake by 33% (from 450 to 300 mg/day) would lower plasma cholesterol level by 3.7 mg/dL (approximately by 1.85%) and a 1% decrease in energy intake from saturated fat decreases plasma cholesterol by 3 mg/dL (approximately 1.5%). Since dietary cholesterol has little effect on plasma cholesterol in most individuals, the population-wide restriction on egg consumption is not justified (McNamara 1997). The same conclusion was drawn by Dawber et al (1982), who showed that differences in egg consumption were unrelated to blood cholesterol level or to the incidence of coronary heart disease. After adjusting for demographics (age, gender and ethnicity) and lifestyle variables (smoking and physical activity), dietary cholesterol was found to be unrelated to serum cholesterol concentration (Song and Kerver 2000). When 116 male volunteers between the ages 32 and 62 years consumed two whole fresh eggs daily for 3 months no

significant changes in mean serum cholesterol were recorded, and there was no significant association between dietary cholesterol intake and either serum cholesterol or triglyceride (Flynn et al 1979). Similarly a recent study involving 37 850 men and 80 082 women concluded that the consumption of up to one egg per day was unlikely to have a substantial overall impact on the risk of cardiovascular disease or stroke among healthy men and women (Hu et al 1999).

Interestingly, recently it has been shown that people who reported eating four or more eggs per week had significantly lower mean serum cholesterol than those eating one egg or less per week (193 mg/dL versus 197 mg/dL, $P < 0.01$) (Song and Kerver 2000). Furthermore, when dietary confounding factors were considered, no association was found between egg consumption at levels up to one egg per day and the risk of coronary heart disease in non-diabetic men and women (Kritchevsky and Kritchevsky 2000). A recent conclusion from a review of epidemiological and clinical data published by McNamara (2000) was that 'for the general population, dietary cholesterol makes no significant contribution to atherosclerosis and risk of cardiovascular disease'. These suggestions are in line with a recent finding that consumption of three eggs per day for 30 days by pre-menopausal women did not increase the risk of developing an atherogenic lipoprotein profile (Herron et al 2002). From another analysis of data summarising 166 cholesterol-feeding studies conducted over the past 40 years in 3500 subjects, it was concluded that there was little justification for restriction in egg consumption for general healthy individuals (McNamara 2000a).

Once the public image of the egg is changed for the better, there are many opportunities to produce 'designer eggs' enriched with various nutrients with health-promoting properties.

Selenium-enriched eggs as a route toward improving human selenium status

Before the advent of commercially available organic selenium for food animal diets, the main problem regarding the enrichment of eggs with selenium was the low efficiency of transfer of inorganic selenium (selenite, selenate) 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 (for review, see Surai 2002). However, the development and commercialisation of the organic form of

Table 6 Selenium in the egg

<i>Organic Se added to the feed (ppm)</i>	<i>Se in egg yolk (ng/g)</i>	<i>Se in egg white (ng/g)</i>	<i>Se per egg (μg)</i>	<i>RDA from one egg</i>
0	298.3	50.7	7.10	11.4
0.2	605.3	193.7	18.04	28.9
0.4	854.0	403.7	30.67	49.1
0.8	1087.3	621.7	43.35	69.4

Source: Adapted from Surai (2000b).

selenium (Sel-Plex™, Alltech Inc, USA) opened a new era in the production of selenium-enriched products. Studies in our laboratory showed that egg selenium content can be easily increased when Sel-Plex™ is included in the diet at a level to provide 0.4 ppm Se (Table 6; Surai 2000, 2000a, 2000b). In fact, Se content in the egg was increased from 7.1 μ g up to 30.7 μ g as a result of dietary supplementation with organic selenium. This finding is in agreement with recent data of Paton et al (2002) indicating that whole egg Se is directly affected by the level of the organic selenium in the diet of the laying hen. As a result, the technology for the production of eggs delivering ~50% of selenium RDA was developed and successfully tested (Surai et al 2000). Currently, companies all over the world market Se-enriched eggs including Mega-Eggs in Ireland, NutriPlus eggs in Malaysia, as well as selenium-enriched eggs in Thailand, Australia and the US. Prices for those eggs varied from country to country and are similar to those for free-range eggs.

In the UK, the only designer egg available through the supermarkets is the 'Columbus' egg produced by the Belgium company Belovo. These eggs, enriched in n-3 fatty acids and vitamin E, first appeared in Belgium in 1997, and since then they have been sold in the UK (1998), Netherlands (1999) and India, Japan and South Africa (2000). Currently production of the Columbus egg exceeds 50 million eggs per year in Europe. These eggs are characterised by a balanced nutritional lipid composition (C18, ω -6: ω -3 = 1:1) and a favourable structural lipid ratio (long-chain PUFA, ω -6: ω -3 = 1:3). When fed to selected groups of people, Columbus eggs have been shown to improve the circulating cell membrane fatty acid composition by favourably altering the ω -6: ω -3 ratio (De Meester et al 1998). The level of alpha-linolenic acid in Columbus eggs is about 12.6% while DHA comprises about 2% of total fatty acids in the egg yolk. Therefore, these eggs could adjust a diet toward recent nutritional recommendations regarding dietary fatty acid profiles. In particular, it is recommended that the linoleic

acid:alpha-linolenic acid ratio in the diet be 5:1–10:1 with n-3 PUFA to provide 0.4%–2% of total energy (FAO 1998).

In this respect it is worth mentioning that recent n-3 PUFA consumption in the UK provides only 0.23% of total energy and in the Netherlands, Belgium, Germany, Ireland and Italy this figure is even lower (Roche 1999). Recently, Columbus eggs were also enriched with selenium, delivering with a single egg more than 50% RDA (35 μ g) of this trace element as well as 10 mg vitamin E (66% RDA) and 75 μ g iodine. It seems that after long discussions about selenium deficiency in the UK, a product is available on the supermarket shelves that can substantially improve Se status of the major part of population. Since these types of designer eggs find their way to supermarket shelves in other countries the selenium status in those countries can also be improved. This could be a result of successful knowledge transfer from developer and producer of the feed additive (Alltech Inc, USA), via scientific evaluation and development of the effective technology of designer egg production (Surai 2002), to the egg producer; and food retailers to consumers. To satisfy consumer demand in the UK, free range Columbus eggs enriched with ω -3 PUFAs, vitamin E and selenium are also on the supermarket shelves.

The advantages of enrichment of the egg yolk with antioxidants include:

- Decreased susceptibility to lipid peroxidation (enrichment of eggs with ω -3 PUFA is associated with increased susceptibility to peroxidation).
- Prevention of fishy taste formation (the fishy taste is associated with products of peroxidation of ω -3 fatty acids).
- Designer eggs could be a good source of antioxidants in the human diet.

Further development of various types of designer eggs could make an important contribution to functional food development with a consequent improvement of the human diet. In relation to selenium, organic selenium in the form of Sel-Plex™ can also be added to diets fed to pigs and broiler chickens to produce selenium-enriched meats; products which are already on the market in Korea. Recent results of Hintze et al (2002) demonstrated that cattle fed diets high in Se from agricultural products can accumulate substantial amounts of Se in beef. Since cattle transfer diet organic selenium to milk, selenium-enriched milk is being considered for improvement of selenium status of children in some countries (Surai 2002). Therefore, it is possible to provide consumers with a range of animal-derived products with nutritionally modified composition in such a way that

Table 7 Major nutrients in a Super egg

Nutrient in the egg	Amount (mg)	% Recommended dietary allowances	Similar amount provided by
Vitamin E	19.3	129	100 g corn oil 150 g margarine 300 g peanuts 1 kg butter 10 kg meat
Lutein	1.91	RDA not known	50 g celery 100 g green peas 200 g asparagus 200 g green pepper 200 g yellow pepper
Selenium	0.032	50	100 g wheat bread 150 g brown bread 500 g meat 1 kg vegetables
DHA	209	100	49 g sardine 165 g Atlantic cod 170 g haddock 180 g carp

Source: Adapted from Surai (2001).

they can deliver a substantial amount of health-promoting nutrients to improve general diet and help maintain good health. Therefore, without changing the habits and traditions of various populations, it is possible to solve problems related to the deficiency of various nutrients, particularly selenium. The consumer will go to the same supermarket to buy the same animal-derived products (egg, milk and meat), and cook and consume them as usual. The only difference will be in the amount of specific nutrients delivered with such products.

If egg selenium content is enhanced along with increased levels of ω -3 PUFAs and vitamin E (Columbus) or vitamin E and specific carotenoids (Super eggs, Table 7; Surai 2001) in levels comparable with RDA, this could further widen opportunities for producers and consumers to meet the specific nutrient demands that aid in maintaining a healthy lifestyle.

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