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Review

Designer eggs: from improvement of egg composition to functional food

P.F. Surai* and N.H.C. Sparks

Avian Science Research Centre, SAC, Auchincruive, Ayr, KA6 5HW, Scotland, UK (fax: +44-1292-525-177; e-mail: p.surai@au.sac.ac.uk)

Diet plays an important role in maintaining health. Among the different products delivering essential nutrients to the body, an egg has arguably a special place, being a rich and balanced source of essential amino and fatty acids as well some minerals and vitamins. This paper focuses on the benefits to the consumer of improving the nutritional quality of eggs by enhancing levels of anti-oxidants and n-3 fatty acids such as docosahexaenoic acid (DHA). The advantages of simultaneous enrichment of eggs with vitamin E, carotenoids, selenium and DHA include better stability of polyunsaturated fatty acids (PUFA) during egg storage and cooking, high availability of such nutrients as vitamin E and carotenoids, absence of off-taste and an improved anti-oxidant and n-3 status of people consuming these eggs. Having reviewed the relevant scientific literature it is concluded that "designer eggs" can be considered as a new type of functional food.

Introduction

Discussions about factors that determine our health started long ago, Hippocrates observing a relationship between health and food choices some 2500 years ago. During the last decade it has become increasingly clear that while our lifestyle (which includes factors such as diet, stress, smoking, medical attention, exercise and genetics) is a major determinant of our health status it is diet that has the pivotal role. The change in focus of the study and practice of nutrition in the USA and Europe from combating nutrient deficiencies to addressing nutrient needs for good health throughout the life [1] reflects this.

Arguably one of the most fascinating ideas in human nutrition is that selected foods and their components can improve physical or mental performance or decrease disease risk [2,3]. Thus, beyond meeting nutrition needs, diet may modulate various body functions and may play detrimental or beneficial roles in the development of some diseases [4]. For example, dietary factors are considered to be major contributors to the leading causes of death of Americans, including coronary heart disease and certain types of cancer [3]. Epidemiological findings, supported by animal studies, have led to recommendations that people should consume at least two servings of fruit and three servings of vegetable daily [5] as well as at least two servings of fish weekly [6]. While findings and reports such as these have had an impact on the type and quantity of the food that many of us eat [7] the majority of adults in so-called developed countries fall well short of meeting healthy eating guidelines. This paper focuses on one potentially important dietary ingredient, the egg. Eggs are of particular interest because they are relatively rich in fatty acids and the associated fat soluble compounds and the type and ratios of fatty acids are, it is now being appreciated, an important determinant of human health.

Diet optimization and human health

Major advances have been made in recent years in our understanding of the molecular mechanisms whereby dietary fatty acids influence the body's metabolism. It has become clear that in addition to their well defined roles in energy metabolism and as constituents of biological membranes, polyunsaturated fatty acids (PUFA) also have specific regulatory functions through the synthesis of different biologically active compounds, including eicosanoids. PUFA may be subdivided into families depending on the position of the double bond in the molecules. Two of the important groups of PUFA in human nutrition are the n-6 or omega-6 fatty acids (the double bond closest to the non-carboxyl end

*Corresponding author.

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is located at the C-6) and the n-3 or omega-3 fatty acids (the same double bound is located at the C-3). The precursors of the n-6 and n-3 family of fatty acids are linoleic acid (LA, 18:2n-6) and alpha-linolenic acid (ALA, 18:3n-3), respectively. These PUFA have to be supplied by the diet [8]. The n-3 and n-6 PUFAs are not inter-convertible in the human body and affect eicosanoid metabolism, gene expression and intercellular cell-to-cell communication [9]. LA and ALA can be elongated and desaturated into their longer-chain active metabolite arachidonic acid (20:4n-6) and eicosapentaenoic acid (EPA; 20:5n-3) and docosahexaenoic acid (DHA; 22:6n-3) [10]. Because these two classes of PUFA are metabolically and functionally distinct and in many cases have opposing physiological effects [9], the absolute level and the balance between n-6 and n-3 PUFA in the diet is considered to be an important determinant of many metabolic functions in the human body (Table 1).

Because the typical 'Western' diet, provides high levels of n-6 PUFAs and low levels of n-3 PUFAs, it is considered to be unbalanced and to be associated with the increased incidences of certain diseases [11]. There are a number of potential solutions to this problem. For example:

1. Increase consumption of fish and fish products. However, world stocks of cold water fish, which are rich in n-3 PUFAs, are decreasing and their farmed equivalent usually contains much lower levels of DHA compared to wild fish [12]. Furthermore, a large proportion (up to 65%) of the population, do not eat fish regularly [13].
2. Use of a capsulated form of DHA or other n-3 fatty acids. This option has the advantage of being able to delivering a known quantity of n-3 PUFA but the capsules can be relatively expensive and some individuals do not like swallowing capsules.
3. Produce designer or so-called functional foods, enriched with n-3 fatty acids. This option has been embraced during the last few years and there are now many products in the market that are enriched with n-3 fatty acids, including various oils, bakery products, infant formula milk, mayonnaise, margarine, salad dressings and others [9]. Among them, eggs could have a special place as an ideal delivery system for n-3 fatty acids.

Another well documented and food-related cause of disease are free radicals (Table 2). Free radicals are implicated in the initiation or progression phase of various diseases, including cardiovascular disease, some forms of cancer, cataracts, age-related macular degeneration, rheumatoid arthritis and a variety of neurodegenerative diseases [14]. In general, it is widely believed that most human diseases at different stages of their development are associated with free radical production and metabolism. Normally, there is a delicate balance between the amount of free radicals generated in the body and the anti-oxidants to protect against them. However, an excess of free radicals, or lack of anti-oxidant protection, will shift this balance producing oxidative stress. Food components can modulate this balance and may thereby influence the rate of aging [15] as well as disease-resistance of the human [5]. The most important step in balancing oxidative damage and anti-oxidant defence in the human body would be to enhance the anti-oxidant capacity by optimizing the dietary intake of anti-oxidants through, for example, increased consumption of anti-oxidant-rich foods. These could be foods natural rich in anti-oxidants as in the case with some fruits and vegetables [5] or through modification as with so-called modified or functional foods.

Functional foods

The concept of healthy food additives has come from Japan in the 1970s with the term 'functional foods' appearing in 1984 [16]. Indeed this 'changing face' of food has led to the development of a new area of food science [17]. The Food and Nutrition Board of the National Academy of Sciences defines a functional food as one that encompasses potentially healthy products providing health benefit beyond that of traditional nutrients it contains [3]. This is in agreement with the data of the recent USA study from written questionnaires completed by 2074 qualified respondents in 1998 indicating that most shoppers believe foods can offer benefits that reach beyond basic nutrition to functional nutrition for disease prevention and health enhancement [18]. However, in the recent survey in the USA, respondents have reported that taste is the most important influence on their food choices, followed by cost [19]. Similarly, in the survey in Ireland, 'quality/freshness of food' was the most frequently selected food choice factor (51%) followed by 'taste' (43%) and 'trying to eat a healthy diet' (36%) [20].

Today, functional foods receive substantial attention [21,22] and represent one of the fastest growing segments

Table 1. Beneficial effects of n-3 fatty acids for human in prevention and management of human diseases [adapted from [9,79]

Disease	Disease
Coronary heart disease	Embolism
Hypertension	Allergic problems
Trombosis	Chronic obstructive pulmonary disease
Type 2 diabetes	Prostate and breast cancer
Renal disease	Immunological functions
Rheumatoid arthritis	Autoimmune disease
Ulcerative colitis	Fetal brain and visual development
Crohn's disease	Improvement of learning ability
Depression	Positive effects on longevity

of the world food industry [16]. For example, dairy products and other processed foods, including mayonnaise, margarine, dressings containing DHA [23] as well as n-3 enriched eggs [24,25] are already on the market in different countries. Se-enriched pork is produced in Korea and there are good prospects of producing chicken meat enriched in Se as well [26]. Anti-oxidant-fortified margarine is shown to be effective in the delivery of vitamins E and C as well as α- and β-carotene to human [27]. In the USA, annual sales of functional food products comprise around $50 billion [16].

Eggs as an integral part of the diet

Hens' eggs have been used as a food by human beings since antiquity. Compared with the egg, no other single food of animal origin is eaten by so many people all over the world and none is served in such a variety of ways. Its popularity is justified not only because it is easy to produce and has so many uses in cookery, but also because of its nutritive quality [28].

Of the three dietary essentials—proteins, fats, and carbohydrates—the egg is composed largely of the first two. Furthermore, the nutritive quality of an egg enhances the value of any food in which it is incorporated. Its wide use in cookery for purposes of leavening, thickening, binding, and emulsifying considerably improves the human diet [29]. Egg proteins are highly digestible containing the most important essential amino acids in a profile that is not dissimilar to the ideal balance of amino acids needed by men and women. Eggs also supply various minerals, some in significant amounts, and contain major vitamins. For example, in a recent study in the USA it has been shown that eggs contributed 10–20% of daily intake of folate and total, saturated and polyunsaturated fat, and 20–30% of daily intake of vitamins A, E and B12 [30]. In this respect, an

Table 2. Free radical involvement in the development of human diseases (adapted from [15,80–83]

Liver	Macular degeneration
Reperfusion	Ocular hemorrhage
Toxic effects of chemicals: halogenated hydrocarbons, quinones, iron, acetaminophen, ethanol	Cataracts
Endotoxin	Muscle
Kidney	Muscular dystrophy
Autoimmune nephrosis:inflammation	Multiple sclerosis
Toxic effects of chemicals: aminoglycosides, heavy metals	Exercise
Lung	Skin
Normobaric hyperoxic injury	Radiation (UV or ionizing)
Bronchopulmonary displasia	Thermal injury
Toxic effects of chemicals: paraquat, bleomicin	Toxic effects of chemicals: tetracyclines stimulating photosensitization
Emphysema	Contact dermatitis
Asbestosis	Porphyria
Idiopathic pulmonary fibrosis	Brain and nervous system
Heart and cardiovascular system	Parkinson's disease
Atherosclerosis	Alzheimer's disease
Hemochromatosis	Tardive dyskinesia
Reperfusion: after infraction or transplant	Neuronal ceroid lopofuscinosis
Selenium deficiency (Keishan disease)	Neurotoxins
Toxic effects of chemicals: ethanol, doxorubicin	Hypertensive cerebrovascular Injury,
Myocardial infarction	Allergic encephalomyelitis
Gastrointestinal tract	Inflammatory-immune system
Reperfusion	Glomerulonephritis
Toxic effects of chemicals: nonsteroidal and anti-inflammatory agents, alloxan, iron	Vasculitis (hepatitis B virus, drugs)
Pancreatitis, Colitis	Autoimmune disease
Blood	Reumatroid arthritis
Malaria	Miscellaneous/general
Various anemias	Aging
Protoporphyrin photooxidation	AIDS, Cancer, Diabetes
Toxic effects of chemicals: phenylhydrazine, primaquine and related drugs, sulfonamides, lead etc.	Inflammation
Favism	Trauma
Fanconi's anemia	Ischemia/reperfusion
Eye	Radiation injury
Retionopathy of prematurity	Rheumatoid arthritis and lupus
Photic retinopathy	Toxic effects of chemicals: alloxan (diabetes), iron overload
	Acute pancreatitis, Amyloidosis

egg can deliver (as % the daily value for a nutrient) protein: 10, riboflavin: 15, vitamin B12: 8, vitamin A: 6, vitamin D: 6, folate: 6, vitamin B6: 4, vitamin E: 3, thiamin 2, zinc 4 and iron 4. Many of those nutrients in the egg can be manipulated by dietary means; however, a real value for improvement of human diet could have only those nutrients which are usually in short supply with other products or have a positive effect on human health when consumed in excess. Among them n-3 fatty acids, vitamin E, carotenoids and selenium have attracted a lot of attention in nutritional sciences.

Omega-3-enriched eggs

Commercial table eggs contain a high proportion of n-6 PUFA (mainly 18:2n-6) but are a poor source of n-3 fatty acids. Attempts to produce eggs high in n-3 PUFA can be divided into two groups. The simplest way is to produce an egg enriched in linolenic acid [24], which is a precursor of DHA and is also considered to have a protective effect against fatal ischemic heart disease [31,32]. For this purpose, the hen's diet is usually relatively rich in flaxseeds, linseeds or their corresponding oils; as a result the egg's yolk is enriched with alpha-linolenic acid (ALA) and the level of DHA is also enhanced [33].

However, given that most of the health promoting properties of n-3 fatty acids are associated with DHA, the health benefits of ALA-enriched eggs could be limited (since the conversion of linolenic acid into DHA in human body is not always effective). This is especially so in the elderly and children when their diets are rich in n-6 PUFAs. The second group or route to enhancing levels of n-3 in the egg, by including pre-formed DHA in the hen's diet, usually in the form of fish (menhaden, herring or tuna) oil, is a more promising one (See [25] for review). However, this may be associated with a pronounced fishy taste in the egg yolk.

Organoleptic quality of omega-3-enriched eggs

The organoleptic quality of omega-3 eggs tends to be similar to regular table eggs although in some cases panellists are able to detect off-flavours [34–36]. A 'fishy' or fish-product related flavour was detected in eggs from hens on diet containing 15–20% flax seed [37,38] and the data of Leeson *et al.* [39] also suggest that high (>10%) levels of flax seed will result in some decrease in overall egg acceptability as assessed by aroma and flavour. This remains a problem associated with the commercial production of this type of product. It has been suggested that the use of combinations of anti-oxidants in the hen's diet could help to suppress these off-flavours [40]; however, high levels of vitamin E did not prevent the formation of off-flavours in hens fed on the high (>10%) flax diet [39].

In general, therefore, fishy taints in eggs are not detectable provided that the hens are fed 5% (or less) flaxseed or low levels of a high quality oil, e.g. 1.5% (or less) menhaden fish oil [41–44]. In this respect, a dried DHA-enriched marine micro-algal product showed promising results [45–56]. The fishy taint can result from rancidity of the n-3 enriched diet, therefore the quality of oils used is important in eliminating off-flavour in eggs. While the oil can be protected with anti-oxidants or micro-encapsulated once the oil is oxidized the addition of anti-oxidants will not reverse this situation.

It is notable that the acceptability of 'fishy' taints varies from country to country. For example, eggs produced in some countries (Chile), where fish meal as well as fish oil are usual components of the chicken diet, contain quite high level of DHA and in many cases have a fishy taste (personal experience of PFS). Generally, the public in Chile are used to this taste and accept it as normal while, for Europeans, for example, it would be unacceptable.

Cooking characteristics of omega-3 eggs, including emulsification capacity, hardiness and springiness of sponge cakes prepared using these eggs, were the same as in ordinary eggs [25]. Data on effects of n-3 enrichment on egg quality during storage are limited and sometimes contradictory. For example, it has also been shown that there is no alteration in fatty acid profile of eggs enriched with n-3 PUFAs during cooking [34] or during storage for 7 weeks at 25°C [47] whereas other studies have reported an increased susceptibility to oxidation [48] during storage and cooking. Enrichment of egg yolk in vitamin E is thought to be an effective means to resolving this problem [48] and has been shown to significantly decrease thiobarbituric acid values (TBARS) in n-3-enriched eggs [49]. In other experiments, yolk TBARS values in n-3-enriched eggs were not significantly different from those in control eggs [50]. However, it needs to be recognized that this parameter depends on the analytical technique used and the level of the egg enrichment with n-3 PUFA. Therefore attention needs to be paid to the organeloleptic properties of n-3-enriched eggs and in particular the relationship between n-3 levels and organoleptic quality.

Health benefits of omega-3 enriched eggs

The major advantage to the consumer of omega-3 eggs is an enrichment of plasma lipids with these fatty acids [33,51,52] and as a result health benefit (Table 1). There are also reports indicating other beneficial effects, including decreased plasma triglyceride concentration [53–54] and lowered systolic and diastolic blood pressures [55–57] and platelet aggregation [58]. In some experiments, even total plasma cholesterol level was reduced [59] due to consumption of modified eggs.

Therefore, consumption of 1–2 omega-3 eggs daily may have health-promoting properties increasing n-3 fatty acid levels in blood lipids and in some cases even reducing cholesterol and triglyceride levels in the plasma. What is also important is that in most studies there were no significant increases in plasma cholesterol or triglyceride levels as a result of consuming even relatively large numbers of omega-3 eggs. However, in a recent study by Lewis *et al.* [59], two of the 25 participants responded to the increase in dietary cholesterol through egg consumption with a significant increase in serum total and LDL-cholesterol. They called these participants "responders", concluding that in a human population there are individuals for whom increased consumption of normal or n-3 eggs is not recommended [60]. This finding may account for the inconsistency of results of the effect of egg consumption on the cholesterol level in the plasma published for the last 20 years.

Generally speaking, however, the results clearly show that eggs enriched with n-3 PUFAs are a valuable source of nutrients, and particularly the n-3 fatty acids of which scientific opinion recommends we increase our intake.

Commercial production of omega-3 enriched eggs

There are various egg types on supermarket shelves in different countries. For example, in the UK, the only designer egg available through the supermarkets is the 'Columbus' egg produced by a 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), The Netherlands (1999) and India, Japan and South Africa (2000). Currently, production of the Columbus egg exceeds 50 millions per year in Europe. These eggs are characterized by a balanced nutritional lipid composition (C18, omega-6:omega-3 = 1:1) and a favourable structural lipid ratio (long-chain PUFA, omega-6:omega-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 omega-3:omega-6 ratio [60]. The level of ALA 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 the fatty acid profile of the diet. In particular, it is recommended LA:ALA ratio in the diet to be 5:1–10:1 and n-3 PUFA to provide 0.4–2% of total energy [61]. 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 such countries as The Netherlands, Belgium, Germany, Ireland and Italy this figure is even lower [10].

Pilgrim's Pride Company, the largest producer of poultry products in North America and Mexico introduced the so-called EggsPlus with an increased level of vitamin E and omega-3 fatty acids. Similar eggs are produced by Gold Circle Farms (containing 150 mg DHA and 6 mg vitamin E, CO, USA) and OmegaTech (USA), produce the so called Gold Circle Farms Eggs. Omega Tech launched the sale of DHA eggs in Germany, Spain, Portugal, Belgium, Norway and Andorra, selling over 100 million eggs in 1996. The contribution that DHA-enriched eggs can potentially make was recognized by their being awarded the 'Most Innovative Finished Food Product Award' in 1996 at the annual Food Ingredients Europe Conference in Paris.

Eggland's Best, Inc. markets premium quality shell eggs under the Eggland's Best brand name [62]. They claim to have increased by 7-fold the generic level of vitamin E, by three-fold the level of omega-3 fatty acids and iodine and to have reduced by 25% the saturated fat when compared with standard eggs. In general, speciality eggs at the US market comprise about 5% and are growing by 1% a year.

The production of designer eggs involves extra cost and they are usually sold at premium prices. The prices could differ substantially, but in the UK they are likely to be not dissimilar from prices currently being paid for free range and organically produced free-range eggs (which are almost twice the price of normal table eggs). In fact, in the USA egg price is substantially higher for the speciality eggs (averaging $2.18/dozen, nutritionally altered eggs $1.81/dozen) compared to white eggs ($1.23/dozen) [63]. The price will ultimately depend in part on the sources of nutrients used in the dietary formulations. As discussed above, enriching eggs with ALA is much easier and cheaper compared to enrichment with DHA. In order to avoid a fishy taste, it is necessary to use stabilized sources of fresh fish oil, which can be relatively expensive. Using algae sources of DHA could be a cheaper alternative. Therefore, there is a need to differentiate DHA-enriched eggs from ALA-enriched eggs. This would reflect the added benefits of DHA-enriched eggs compared to ALA-enriched eggs. It appears that consumers are ready to pay extra for designer eggs provided that they understand the possible health-promoting properties. For example, a survey conducted in five major Texas cities with over 500 consumers indicated that 65% of consumers were willing to purchase n-3 fatty acid-enriched table eggs and, of these, 71% were willing to pay an additional $0.5 per dozen [44].

Other types of designer egg

In the recent USA survey, most modifications to the nutritional profile of eggs were associated with decreased cholesterol, fat or calories or increased vitamin E [62]. However a substantial increase in nutrients was obvious only for folate (2-fold) and vitamin E (up to 6-fold). Our recent results [26,64,65] showed that the inclusion of organic selenium in the chicken diet could substantially increase the accumulation of this trace element in the egg. Indeed the production of Se-fortified eggs is extremely simple: when Se supplementation of the diet is at a level of 0.4 mg/kg diet in the form of Se-enriched yeast, an egg would contain approximately 30 μg of Se (Table 3) which is about 50% of daily requirement. This could be used to improve the Se status of the population in many countries including Scotland where the selenium content of the diet meets only 50% of the requirement [66]. This valuable option awaits response from the food industry.

It has been shown that eggs produced by hens fed 5.0% conjugated linoleic acid (CLA) contained 310–365 mg of CLA per egg [67] providing a substantial amount of CLA in human foods. However the daily requirement in this important compound has not been established yet. Furthermore, CLA can negatively affect general egg quality [68].

Development of an egg enriched with Omega-3 PUFA, selenium, carotenoids and vitamin E

In many respects, the nutrients in eggs are a feature of the diet. For example, unlike eggs from birds fed a manufactured diet, analyses of eggs obtained from wild and free-range birds [69,70] showed very high concentrations of n-3 fatty acids, vitamin E and lutein. It was decided, therefore, to produce, under commercial conditions, a table egg that had enhanced levels of these components and also of selenium (Se). The concept was 'healthy eggs from healthy birds' since these four nutrients are as important for the hen's health as for human health.

By manipulating the feed of laying hens it was possible to enhance the levels of Se, vitamin E, lutein and DHA by 7.7-, 26.8-, 15.9- and 6.4-fold, respectively. A single designer egg could therefore contain 50% of the RDA of Se, 100% of the RDA of long chain n-3 PUFAs, and 150% of the RDA of vitamin E. It would also supply 1.91 mg lutein (no reference nutrient intake has yet been established) (Table 4). A human trial demonstrated that the consumption of sthese modified eggs (an egg per day during 8 weeks) was associated with a significant increase in α-tocopherol, lutein and DHA concentrations in plasma (Figs 1 and 2). Our results also indicate that the two major anti-oxidant constituents of the egg, vitamin E and lutein, were stable during egg boiling [71]. In this experiment, a combination of high levels of two anti-oxidants, vitamin E and lutein, in the designer eggs significantly decreased MDA formation as a result of Fe-stimulated lipid peroxidation, in spite of the high content of the highly unsaturated DHA in hens' eggs.

The major advantages of the combination of DHA and anti-oxidants in the egg yolk are:

Table 3. Effect of selenium dietary supplementation on its content in the egg (adapted from [26])

Organic Se added to the feed (ppm)	Se in egg yolk (ng/g)	Se in egg white (ng/g)	Se per egg (μg)	RDA from one egg (%)
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

RDA (USA) for selenium: men 70 μg/day; women 55 μg/day; average 62.5 μg/day.

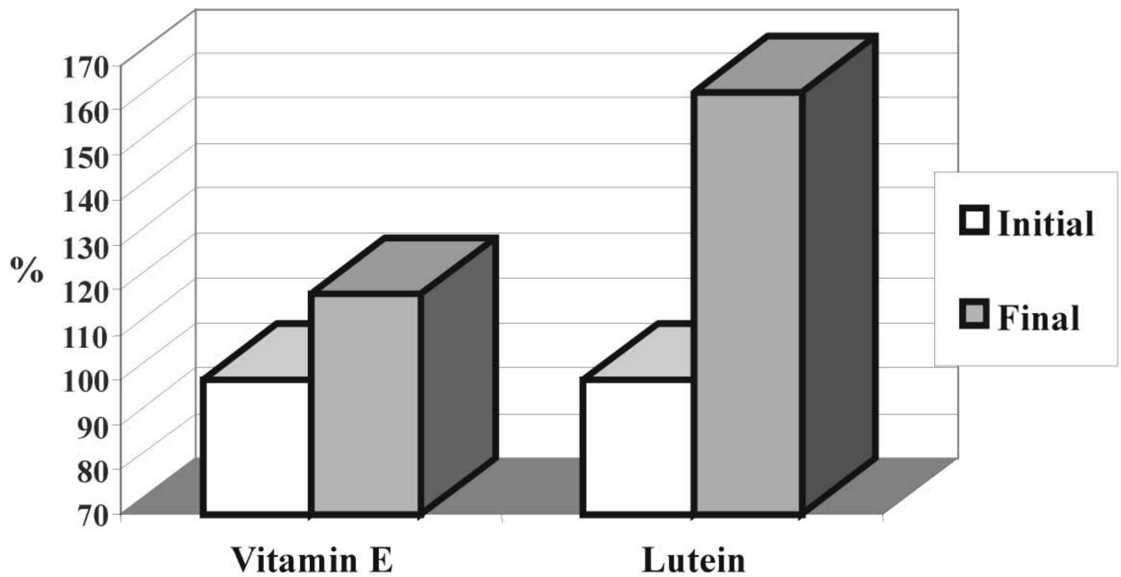

Figure 1. Effect of super egg consumption during 8 weeks on vitamin E and lutein levels in human plasma (adapted from [71])

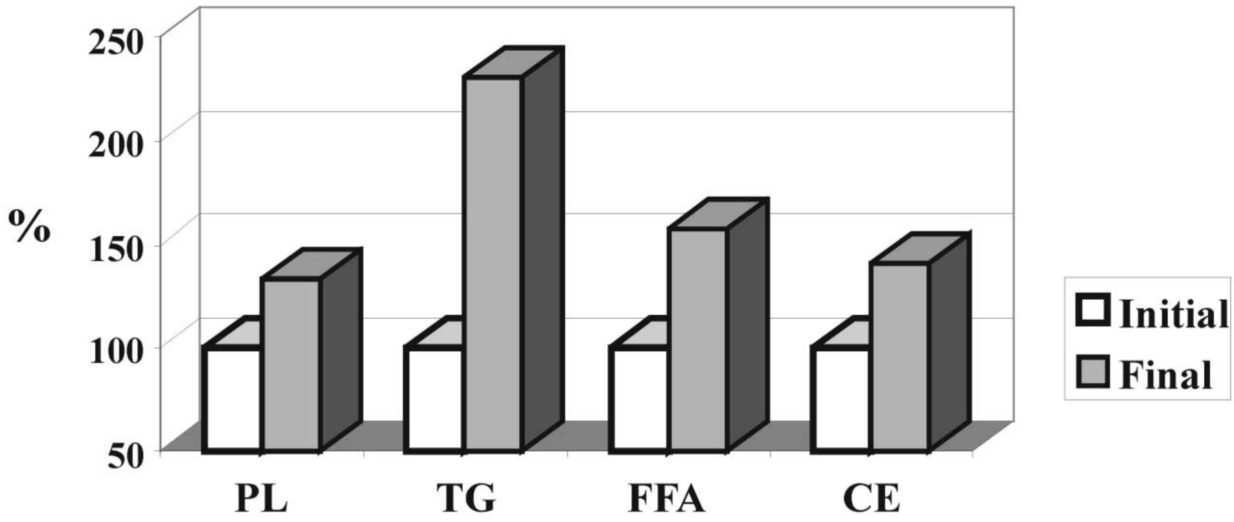

Figure 2. Effect of super egg consumption during 8 weeks on docosahexaenoic acid levels in human plasma. PL, phospholipid; TG, triacylglycerol; FFA, free fatty acids; CE, cholesterol ester (adapted from [71]).

Table 4. Major nutrients in a super egg

Nutrient in the egg	Amount (mg)	% Recommended dietary allowances	Similar amount provided by:
Vitamin E	19.3	150	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

Table eggs contain 0.72 mg vitamin E, 0.12 mg lutein, 0.004 mg selenium and 32.4 mg DHA.

1. vitamin E, lutein and Se protect DHA from oxidation during absorption and metabolism thereby preventing a 'fishy' taste formation;
2. egg yolk lipids are necessary for the efficient absorption of vitamin E and lutein in human intestine (6 g lipids in the egg yolk is sufficient amount of lipids needed for an efficient absorption of vitamin E and lutein in the human intestine) [72];
3. lutein interacts with vitamin E and phospholipids, increasing the yolk's anti-oxidant potential and improving egg storability;
4. Se as an integral part of the anti-oxidant enzyme glutathione peroxidase, protects intestinal membranes against lipid peroxidation during DHA digestion;

Since natural anti-oxidants play important roles in preventing stress-related diseases, the eggs, either whole or as processed products, could be of great importance to people living in polluted areas, (e.g. Chernobyl, Ukraine) and in areas with very low temperatures (e.g. Polar expeditions) and extreme conditions (e.g. submarine teams). Similarly, they could benefit the compromised host (e.g. very young, the elderly and pregnant women).

Eggs as a functional food

Analyses of recent literature and our own research allowed us to arrive at the conclusion that eggs ideally fit the requirements of a functional food. For example, the levels of certain nutrients (vitamin E and DHA) could be increased in the egg to such an extent that consumption of a single egg could deliver these nutrients in amounts comparable or higher than daily requirement [71]. However, a significant barrier to increasing egg consumption in western countries is the perception that egg consumption is associated with a rise in blood cholesterol levels [73] and as a consequence is deleterious to health and life expectancy. In this respect, expert opinion on the role of dietary cholesterol in the development of heart diseases has changed recently, indicating that, for the general population, dietary cholesterol makes no significant contribution to atherosclerosis and risk of cardiovascular disease [74]. Furthermore, results of many studies [9,75,76] have shown that relatively large numbers of eggs can be consumed without any significant changes to plasma cholesterol or other lipid components. This should improve the image of eggs. In this respect, eggs, which are consumed regularly by most of the population, when enriched with DHA, vitamin E, lutein and selenium, are capable of substantially improving the diet.

Recently, six major targets in relation to functional food science have been identified [4]: gastro-intestinal functions; redox and anti-oxidant systems; metabolism of the macronutrients; development in foetal and early life; xenobiotic metabolism and its modulation; and mood and behaviour or cognition and physical performance. As has been shown above, designer eggs can contribute to several mentioned categories: redox and anti-oxidant systems (an egg delivers three anti-oxidant components, including 150% RDA in vitamin E, 50% RDA in Se and a substantial amount of lutein), development in foetal and early life (an egg delivers a minimal RDA for DHA, which is an essential element of the baby brain development) and mood improvement (an egg delivers 50% of RDA in Se, which is considered as having an effect on human mood). Beyond this, a range of bioactive peptides in the egg have been characterized with anti-hypertensive, phagocytosis-stimulating and opioid properties that may be beneficial for humans [77]. Furthermore, eggs can serve as an important source of nutraceuticals and pharmaceuticals [29], including immunoglobulin Y production, use of a protein product derived from egg shell membranes and phagocytosis-stimulating peptides from egg yolk [77] in medical practice. In addition, egg consumption may be also of interest in regulating aspects of glucose metabolism [78]. These and other options of egg use in the human diet need further investigation. Indeed, most studies, including our own 8 week study, with designer eggs have been conducted during a limited length of time and it is not clear what kind of benefit we could expect if, for example, designer eggs were consumed as part of the diet for 6–12 months.

Commercially, it is possible to produce designer eggs enriched with many different nutrients simultaneously or with a single nutrient depending on the consumer demand. As a result, price for the production of such eggs could substantially vary. The idea of egg enrichment with n-3 fatty acids simultaneously with anti-oxidants and other vitamins has recently been used to produce VITA Eggs by Freshlay Foods (Devon, UK). They state that the eggs were enriched by n-3 fatty acids, Se, vitamins D, E, B12 and folic acid.

Therefore, the ability of the egg to be used a functional food has been established; now what is required is education of the consumer as to its potential benefits. Indeed, many categories of people will benefit from using designer eggs as part of their everyday diet. However, more research should be done in this fascinating area to improve designer egg quality and assess long-term effects of their consumption and ultimately to convince customers of the benefits of eating these eggs.

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