



Conference on ‘Changing dietary behaviour: physiology through to practice’ Symposium 3: Novel methods for motivating dietary change

Approaches to influencing food choice across the age groups: from children to the elderly

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Nutrition across the lifespan encompasses both preventative and treatment options to maintain health and vitality. This review will focus on the challenge of overconsumption of energy relative to energy expenditure and the consequent development of overweight and obesity, since they are responsible for much of the burden of chronic disease in the developed world. Understanding the mechanisms of hunger and satiety and how particular foodstuffs and nutrients affect appetite and motivation to eat is important for evidence-based interventions to achieve weight control and design of community-wide dietary strategies that reach across the lifespan. Food reformulation for appetite control and weight management requires a knowledge of the mechanisms of hunger and satiety, how food interacts with peripheral and central regulatory systems, and how these interactions change across the lifecourse, allied to the technical capability to generate, evaluate and develop new ingredients and foods with enhanced biological potency based on these mechanisms. Two European Union-funded research projects, Full4Health and SATIN, are adopting these complementary approaches. These research projects straddle the sometimes conflicted ground between justifiable public health concerns on the one hand and the food and drink industry on the other. These multi-disciplinary projects pull together expertise in nutrition, neuroimaging, psychology and food technology that combines with food industry partners to maximise expected impact of the research. Better knowledge of mechanisms regulating hunger/satiety will lead to evidence base for preventive strategies for the European population, to reduction of chronic disease burden and to increased competitiveness of European food industry through the development of new food products.

Food choice: Satiety: Obesity: Reformulation: Appetite: Full4Health: SATIN

Obesity and overweight are more than ever one of the most compelling nutrition issues worldwide. The world is facing an epidemic of non-communicable disease (NCD), which kills more than 36 million people per year (63 % of all-cause mortality). The WHO Global action plan for the prevention and control of NCD 2013–2020 identifies four main types of NCD: CVD (heart attacks and stroke); cancers; chronic respiratory diseases (such as chronic obstructed pulmonary disease and asthma); diabetes. Modifiable behavioural risk factors include unhealthy diet, physical inactivity and harmful use

of tobacco and alcohol. For three out of four of these major health issues, obesity is also a major risk factor, further emphasising the role of diet, both composition and quantity, in global ill-health. Overconsumption of energy is the root cause of the increasing prevalence of global obesity, with dietary habits perpetuating health inequalities. Food choices, especially in an environment of ready availability and plentiful supply of cheap ready to eat foods, should be a primary focus of preventative measures. A successful strategy to guide dietary choice towards healthier options and lower energy intake

Abbreviations: EFSA, European Food Safety Authority; NCD, non-communicable disease.

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would counter the present trajectory of obesity prevalence, improve outcomes on weight loss and weight maintenance diets, promote active and healthy ageing, and reduce the burden on health care budgets.

The obesity problem

The growing global obesity crisis demands a multi-disciplinary preventative and therapeutic strategy involving all the potential tools at our disposal. The prevalence of obesity worldwide (defined as BMI ≥ 30 kg/m²) increased from 5 and 8 % for adult men and women, respectively, in 1980, to 10 and 14 % by 2008. This equates to 205 million men and 297 million women with obesity⁽¹⁾: more than 0.5 billion adults over age 20 years worldwide, and accounts for more than one in four adults in the USA. The 2008 figures for overweight (BMI ≥ 25 kg/m²) were 34 and 35 %, respectively. The toll exacted on health (morbidity) and lifespan (mortality) is considerable. As alluded to earlier, overweight and obesity are associated with increased risk of CVD, stroke, type 2 diabetes and a number of cancers, with estimates of nearly 3 million deaths each year and over 30 million disability adjusted life years lost globally, reflecting an integration of premature death and time spent disabled by disease.

Energy balance controls weight gain

Weight gain, overweight and obesity cannot exist in the absence of positive energy balance, i.e. energy intake (energy consumed as food and drink) exceeding energy expenditure (the sum of RMR, thermogenesis and physical activity). Despite the undoubted complexity of the biological, psychological, social and economic factors that underlie the obesity epidemic, it is incontrovertible that excess consumption of energy relative to energy expenditure is the root cause of body fat accumulation. The increase in overweight and obesity in the past 30 years referred to earlier, represents the outcome of gene–environment interactions where propensity to accumulate excess food energy as fat in those with a genetic predisposition is exposed by our present obesogenic environment. Important components of this environment include the food we eat, the context within which we consume it, work–life balance, low activity lifestyles, etc. Plausible responses for policy take-up, as identified in the UK Foresight project report⁽²⁾ Tackling Obesities: Future Choices accordingly include addressing the availability of fattening foods and drinks (energy in) and the scope for physical activity in our everyday lives (energy out). These potential preventative measures, along with initiatives targeting ‘early years’ and ‘working lives’ have also been adopted by the Scottish Government in its policy to tackle obesity within the Scottish population⁽³⁾.

Dietary strategies to influence food choice

There are many ways to influence food choice, with emphasis in the present paper on food-based strategies that

can impact on appetite control. We will discuss: (i) food reformulation, (ii) food approaches and (iii) health claims, with reference to the present EU grant awards that focus on food and energy balance.

Conventionally, the term food reformulation refers to modification of the composition of individual processed food products, or product ranges, and especially their content of fat, sugar, salt, micronutrients such as minerals and vitamins, or bioactives such as phytochemicals. Where there is the potential for health benefit, this reformulation is desirable in a public health and policy context^(4,5), as opposed to purely at a commercial level, especially where products of low nutritional quality are concerned. For example, salt reduction targets have been applied across a wide range of food categories with the aim of reducing blood pressure and the risk of heart disease and stroke at a population level. Since processed foods contribute the majority of dietary sodium,^(6,7) governments, agencies and the food industry are working together to address this as well as other dietary goals (e.g. *trans*-fatty acids and energy). This approach is exemplified in the UK by the Department of Health’s Public Health Responsibility Deal⁽⁸⁾, and regionally by the EU platform for action on diet, physical activity and health⁽⁹⁾. However, the efficacy of such voluntary initiatives engaging the food industry in addressing public health priorities has been questioned⁽¹⁰⁾. The issues surrounding reformulation of processed food products while maintaining fundamental properties such as texture, shelf-life, and above all, palatability, and thus consumer acceptability, are complex; reducing the content of one component usually requires substitution with another, which may dilute the intended benefit.

Less high on the recent agenda, but being recognised increasingly for its potential efficacy as a strategy to limit overconsumption of energy, is food reformulation for appetite control^(2,11). This concept can involve exploitation of the natural properties of macronutrients, or specific/potential food components, in the preparation of foods or drinks that engage with our endogenous appetite/energy balance regulatory systems. Manipulation of regulatory molecules or tissues by dietary components that are able to limit, or potentially bolster, overall energy intake, could find application at either end of the nutritional spectrum. The nature of this engagement with our innate regulatory systems could be psychological, physiological, endocrine, metabolic or neural, or a combination of these, encompassing the gamut of food–gut–brain interactions that we encounter in our present food environment. This range of interwoven targetable biological processes is exemplified in the concept of the satiety cascade^(12–15).

Obesity treatment

Prior to assessing food reformulation as a route to reducing energy intake, it is worth considering the present status of surgical and pharmacological interventions, and conventional energy restriction. Different forms of bariatric surgery can result in substantial and long-term



weight reduction and resolution of type 2 diabetes, but vary in effectiveness and risk. Recent meta-analysis of over 160 000 patients with a starting BMI of 45.6 revealed an overall mortality rate of 0.08 % within 30 d and 0.31 % after 30 d, and BMI reduction of 12–17 points 5 years post-surgery⁽¹⁶⁾. Complications were reported for 17 % of surgeries and 7 % required re-operation. Gastric bypass and sleeve gastrectomy were more effective for weight loss than adjustable gastric banding, but the bypass was associated with more complications, and whereas banding had lower mortality and complication rates, the re-operation rate was higher. In the Swedish Obese Subjects study, over 2000 obese subjects underwent bariatric surgery (13 % gastric bypass; 19 % gastric banding; 68 % vertical banded gastroplasty)⁽¹⁷⁾. Body weight changes at 2, 10, 15 and 20 years were –23, –17, –16 and –18 %, respectively, and were accompanied by reduced overall mortality, diabetes, myocardial infarction, stroke and cancer. Although surgery is an effective route to tackle severe obesity, it is clearly not an appropriate intervention for mild obesity or for individuals progressing through overweight. Drug therapies are an important option for obese patients for whom lifestyle interventions alone are ineffective⁽¹⁸⁾. Systematic review of drugs currently approved for long-term use in adults in the USA (prescribed along with lifestyle intervention) revealed weight loss relative to placebo at 1 year ranging from 3 % for orlistat and lorcaserin to 9 % for top-dose phentermine plus topiramate. At least 5 % weight loss, a level taken to be clinically meaningful, was achieved in 37–47 % of patients for lorcaserin, 35–73 % for orlistat and 67–70 % for top-dose phentermine plus topiramate.

Despite the undoubted effectiveness of surgery and some promising outcomes from drug therapy, dieting remains the most common approach to controlling body weight, with a substantial minority of the population of developed countries attempting such cognitive restraint of nutritional intake. For many people, moderate weight loss through direct energy restriction is achievable in the short-term, and rapid weight loss can be achieved through regimens such as a very low-energy diet⁽¹⁹⁾, but most find it very difficult to keep weight off in the medium-to-long term and will eventually regain the weight that has been lost, and may even exceed their original weight when they fail to sustain a diet. Strong hunger pangs and diminishing return from the same level of restriction as reductions in metabolic rate ensue may contribute to subjects coming off the diet. Repeated bouts of weight loss and regain can result in the so-called yo-yo weight cycling. Strategies for avoiding or limiting weight regain after very low-energy diet or low-energy diet are now becoming clearer, with anti-obesity drugs, meal replacements and high-protein diets improving weight-loss maintenance⁽¹⁹⁾. Accordingly, a major goal is to develop strategies, possibly combining several interventions, which produce sustainable weight loss with a dietary and/or behavioural intervention that individuals can adhere to (compliance).

An alternative dietary strategy to overt energy restriction may be to exploit the natural properties of specific

food components, and the way in which those components interact with physiological and metabolic bodily systems, to limit intake. Diet design or food reformulation that makes use of, for example, differentially satiating macronutrients or specific components that target aspects of the satiety cascade^(12–15) have been shown in experimental settings to support both weight loss^(20–21) and weight maintenance after weight loss⁽²²⁾. Crucially, these outcomes can be achieved under *ad libitum* feeding conditions. Although such interventions may not be powerful enough to make a significant impact of pre-existing obesity, this strategy may still be efficacious in that proportion of the population where body adiposity has not yet become a clinical problem, but where support in limiting overconsumption of energy would be helpful. Although food is plainly a part of the problem in obesity due to overconsumption of energy, by exploiting the food–gut–brain axis, could food also become part of a preventative solution for the future?

The changing dietary landscape

Primary agricultural production changed almost beyond recognition during the course of the 1900s, with mechanisation, intensification, changes in scale, accelerated selective plant and livestock breeding, and increasing application of a range of chemicals to promote growth or reduce wastage. Allied to the push for post-World War II, food security came as a revolution in food retailing and technical innovation, including widespread refrigeration that saw a rather limited, local and seasonal supply of food steadily transformed in scope and product range into the food environment that we are familiar with today. However, in parallel with the expansion of product ranges and year-round sourcing of fresh global produce, food has become progressively cheaper over the decades, representing a declining proportion of household disposable incomes; the share of income spent on food in the US fell from 17.5 to 9.7 % between 1960 and 2007⁽²³⁾. One of the drivers of the revolution in choice, shelf-life and quality has been food processing, which has allowed food to be inserted into busy lives and lifestyles with minimal requirement for time-consuming preparation of meals from raw ingredients. Highly processed foods contribute between 60 and 80 % of mean energy intake in some European countries⁽²⁴⁾, although the degree of processing is not a major determinant of nutrient contribution to the diet or its healthiness⁽²⁵⁾. Significantly, in the 30 years to 2008, consumption of food prepared outside home in the USA increased from 18 to 32 % of total energy intake⁽²⁶⁾. It seems unlikely that such trends are going to be reversed in the foreseeable future. Fat is the most energy-dense macronutrient, and the dual pressures of increased demand for convenience but at decreasing cost to the consumer have given rise to increased incorporation of fats and sugars into many processed food products, with these ingredients having a relatively low price per energy, compared, for example, with fresh fruit and vegetables⁽²⁷⁾.

Food approaches

The increasing prevalence of NCD and the probability that diet (and specifically the comparatively recent shift towards processed foods high in salt, fats and sugar) is contributing to these problems has led to population-level dietary goals, such as the Scottish Diet Action Plan⁽²⁸⁾. Monitoring over the intervening period following the adoption of this plan, however, has indicated that progress against these (Scottish) dietary targets was limited⁽²⁹⁾. Progress towards current UK recommendations has also been limited⁽³⁰⁾. This is emphasised by the observation that when the National Food and Drink Policy for Scotland Recipe for Success was launched in 2009⁽³¹⁾, and the targets were replaced by Revised Dietary Goals for Scotland⁽³²⁾, many of the aspirations for population-level consumption of fruit and vegetables, fats, sugar and salt were unchanged. In both Scotland and the UK, the strategy being pursued in trying to sustain momentum towards these targets is partnership working in food reformulation between government agencies and the food and drink industry. Similar strategies are now increasingly influencing the research agenda; accordingly, understanding the links between diet and health, and the potential for food reformulation using both existing and novel dietary components, are central concepts informing the Scottish Government strategic research programme⁽³³⁾, the UK BBSRC strategic research priority⁽³⁴⁾, and much European Commission-funded research⁽³⁵⁾ in both Framework Programme 7 and Horizon 2020.

Energy balance, hunger and satiety

Food intake is a process that clearly needs to be regulated with some precision, as unless energy intake matches energy expenditure in the medium-to-long term, wasting and even death will ensue. However, overconsumption of energy relative to energy expenditure does not carry such immediate or drastic consequences. Indeed, a state of positive energy balance when food was freely available would be likely to be advantageous in an evolutionary context, but less so in the current environment. The mismatch between the periodicity of energy intake and that of energy expenditure highlights the complex processes that need to be integrated for body weight to be relatively stable over extended periods, and the remarkable accuracy of the regulatory systems involved. Energy intake generally consists of a number of meals and smaller snacks, as well as energy beverages, which can vary considerably in energy density and macronutrient composition. Energy intake is thus heavily patterned across the day, and variable between days. Energy expenditure is both continuous, in terms of BMR, and patterned, due to thermogenesis and physical activity, which vary across a 24 h cycle, and day-to-day depending upon lifestyle and habit (e.g. weekdays *v.* weekends). Maintaining a relatively stable body weight with these inputs and outputs requires an effective regulatory system. Some components of this system impinge upon our consciousness prior to, during or after meals; for example, the output

of gastrointestinal mechanoreceptors, whereas the majority proceed largely unperceived. The integrated system encompasses satiety and hunger signalling from the gastrointestinal tract, whereas hormonal signals from adipose tissue convey information about the size of adipose tissue stores and flux into and out of these stores. The plethora of neural, metabolic and hormonal information originating below the neck is then integrated in key brain regions, including the hindbrain, hypothalamus and forebrain reward systems. The system generally reflects the precedence outlined earlier, being more focused on countering negative energy balance than overconsumption of energy. Superimposed on short-term and longer-term physiological hunger signals, are psychological inputs. Identifying how these very different inputs are integrated, how the system responds to feeding, and how it changes as we age and develop, is likely to be critical to tackle chronic diet-related disease. There are numerous, excellent, comprehensive reviews of energy balance regulation and the molecules and tissues involved^(36–38), and it is not possible to cover this system more than superficially in the present paper. Instead, this review will focus on the potential of exploiting components of the satiety cascade in food reformulation for regulated energy intake.

The psychological, physiological, neural and metabolic determinants of hunger and satiety are either the subject of, or underpin, two major inter-linked EU-funded research projects, Full4Health⁽³⁹⁾ and SATIN⁽⁴⁰⁾. Full4Health primarily focuses on mechanisms of hunger, satiety and feeding behaviour in cell systems, animal models and human volunteers, and seeks to grow the evidence base in this area. The project partners are mainly academic laboratories drawn from a range of bioscience disciplines. SATIN is more heavily orientated towards the application of scientific knowledge in food reformulation for overall reduction in energy intake. Here the composition of the consortium is deliberately skewed towards industrial partners, large and small, allied to academic partners with an interest in reformulation. The SATIN project is attempting to establish proof-of-principle for the health benefits of foods with enhanced satiety properties.

Mechanisms and targets: the Full4Health project

As outlined earlier, Full4Health brings together a range of European laboratories and commercial organisations to examine the effects of diet, dietary components and food structure on mechanisms of hunger, satiety and feeding behaviour. The project encompasses the gut and the signalling systems linking it to different brain regions. Although it is not an obesity project *per se*, the project aims to assess the efficacy of exploiting hunger and satiety processes in addressing obesity, while also bringing mechanistic insight to bear on related chronic metabolic disease and undernutrition. The themes that run through the project include lifecourse, neuronal, hormonal, molecular, physiological and behavioural responses to food at the level of the gut and the brain,

communication between these two key players, psychology, and application of imaging and other cutting edge technologies. Physiological, metabolic and psychological responses to food are likely to change with development and age, which will impact on food choices and preferences. This is a critical issue in the battle against food intake-related chronic disease, most commonly driven by overconsumption, but also in consideration of relative undernutrition in the elderly and clinically compromised.

Critical research questions at different levels of the food–gut–brain interaction are being investigated in both human volunteers through dietary, supplementation and exercise intervention studies, and in laboratory animals. In human volunteers, responses to diet are being investigated from childhood through to the elderly, along with responses to exercise-induced energy deficit and investigation of the relative importance of dietary protein in determining energy intake (see later). Parallel mechanistic study in laboratory animals examines very early-life nutritional programming events for impact on the development of gut–brain signals and translation into life-long perturbations in feeding behaviour and energy balance, and the impact of bioactive compounds from food or gut origin, and food structure, on nervous activity and secretion of hormones from the gastrointestinal tract. Multiple brain regions and signalling molecules of both peripheral and central origin are involved in these processes, and communicate to signal and integrate hunger and satiety, including hindbrain relays, hypothalamic and forebrain structures.

Food reformulation: the SATIN project

The rationale underpinning the complementary SATIN project is that by exploiting different components of the satiety cascade⁽¹⁵⁾ it should be possible to formulate and develop, through to production, new foods and diets that target long-term regulation of appetite. The reduction in hunger could be effected either by accelerating satiety within the meal or by enhancing satiety between meals. The former outcome would have the potential to reduce meal size, whereas the latter could not only lengthen the inter-meal interval but also reduce the likelihood of snacking between meals. The key issue will be whether these biological effects and the changes that they could potentially induce are able to deliver a reduction in overall energy intake in the medium-to-long term, i.e. are a legitimate approach to weight management and health promotion. To achieve this, the call text for this funding stipulated a model whereby academia and industry would work together, and within which a substantial tranche of funding would fund small-to-medium-sized enterprises to deliver innovation and technological advance in commercialisable finished products with established appetitive properties and nutrient bioavailability. The route to production of functional foods with enhanced satiety properties will involve novel processing methods that modify food structure.

To deliver on this vision, SATIN will screen novel food structures through advanced technology *in vitro*

models to identify lead products according to their satiating potential. Food-processing technologies will be applied to active ingredients bringing about changes in food structure to generate novel satiety enhancing ingredients, which will then be taken forward for safety testing, sensory evaluation and consumer response. The performance of potential products in terms of objective biomarkers of satiety and nutrient bioavailability will be examined in human volunteer studies. This will establish efficacy in within-meal satiation, post-meal satiety and/or reduced appetite in short- to medium-term trials. Longer-term trials will establish enduring effects of individual food products on satiety, potential to induce weight loss and contribute to the proof-of-principle that consumption of a diet made up predominantly of such products would have long-term health benefits for the consumer.

Health claims and the consumer

Generating sustained behaviour change at a population level is recognised as a major challenge for many policy areas, including those in the public health arena, where public responses to generic messages can be very variable. Long-term reductions in overall energy intake will require widespread behaviour change, but our present understanding of how to deliver such dietary behaviour change in a sustainable manner is limited. No single intervention is likely to provide the solution to this particular challenge. In particular, nutritional education alone is increasingly recognised as being unlikely to deliver the scale of change required, and reformulation of staple foods may be a useful additional approach⁽³⁰⁾. In the context of dietary behaviour change, some individuals are motivated to seek out ‘healthy’ foods for themselves and their families, and here public health messages may be effective, whereas at the other end of the spectrum are individuals who either do not see the point of the recommended change or are uninterested. Avoidance of ambiguous, contradictory and negative messages will support positive outcomes from public health campaigns, but the barriers that prevent individuals putting desired changes into practice, even if they want to, will remain substantial⁽⁴¹⁾. Reformulation of the food supply focusing on processed food may be a viable option to support reductions in overall energy intake throughout the population, whether through voluntary product selection or a ‘health by stealth’ approach⁽⁴²⁾.

The potential to develop foods that work with the body’s natural regulatory mechanisms is an appealing concept. Foods or dietary supplements with enhanced satiety properties will clearly be attractive to that sector of the population looking to address body weight issues by reducing their overall energy intake. As a consequence, marketing a product as being ‘more satiating’ or ‘reducing hunger’ will likely give that product and its manufacturers a commercial advantage in this sector. Besides the obvious direct effect on food intake, enhanced satiety could promote the dietary and body weight aspirations of consumers indirectly by a variety

of other routes⁽⁴³⁾. Given the potential of this approach, there is a growing need, as in other 'functional' food sectors, to protect the consumer from bogus or ill-founded health claims on commercial products. This requirement is increasing as foodstuffs, dietary supplements and food ingredients become more diverse, as new food components and products are developed, and as access to unsubstantiated or even deliberately misleading information via the internet and other media increases. In Europe, the responsibility for policing such 'health claims' falls to the European Food Safety Authority (EFSA). EFSA is an independent agency, set up more than a decade ago, with its own management board. It is funded via the EU budget and, although separate from the European Commission, European Parliament and EU Member States, delivers an annual work programme agreed with these organisations. EFSA's Scientific Committee and panels of independent scientific experts deliver objective scientific advice on risks associated with the food chain (risk assessment) for Europe's decision-makers in the areas of food and feed safety, nutrition, animal health and welfare, plant protection and plant health. As part of this remit, EFSA publishes scientific 'opinions' on the substantiation of health claims proposed for different dietary constituents. Although the need to protect the consumer and maintain confidence in the food supply chain is paramount in this authorisation process, support for innovation in the agri-food sector is also relevant to the overall process.

In the context of food-related health claims addressing hunger, satiety, energy intake and ultimately body weight, the perspective of the consumer is especially important, and has been well summarised⁽¹⁴⁾. Foods for which a scientific evidence base could be generated in support of a beneficial interaction with physiological satiety systems might be said to have proof of concept, but this might not translate into success in terms of effects on energy consumption or weight management in any individual. The consumer must be able to trust health claims of beneficial effect on energy balance, but also needs to understand the limitations and context of valid claims, since a range of different modes of physiological action are possible. This makes the wording of claims, within the limitations of the supporting scientific evidence, of utmost importance⁽¹⁴⁾. The position of EFSA on health claims relating to appetite and weight management was set out in the 2012 Scientific Opinion entitled Guidance on the scientific requirements for health claims related to appetite ratings, weight management and blood glucose concentrations⁽⁴⁴⁾. This Opinion effectively prescribes that claims on 'appetite rating' (and thus energy intake) should be contingent upon a resultant decrease in body weight, which itself must be a sustained effect of continuous consumption of food over a 12-week period for weight loss or 6 months for weight maintenance after weight loss. The level of supporting evidence required to substantiate an appetite-related health claim is therefore very high, and may preclude a single functional food receiving such an approval, it being unrealistic to expect a food or constituent to be consumed continually over such periods. There are likely to be implications here for innovation in the food and drink,

and biotechnology, sectors in Europe, and thus for efforts to support individual- and population-level reductions in energy intake.

Reformulation

It may be illuminating to consider how EFSA health claim guidelines have been applied to two dietary components that have some of the strongest credentials as likely satiety enhancers. These are dietary protein, a major focus of the Full4Health project, and dietary fibre, one of the primary classes of ingredient of interest to commercial and academic partners in the SATIN project.

Dietary protein

The potential to exploit protein-induced satiety (reduce hunger and promote fullness) as a route to reduce energy intake while eating to appetite is a key component of the Full4Health project, and has been the subject of intensive investigation worldwide⁽⁴⁵⁾. The fundamental basis of this interest is that while the dietary macronutrients have different energy densities (fat being double the energy density per gram protein or carbohydrate), they also have different effects on satiety, with protein being most satiating. Thus a combination in dietary fat of high-energy density and low satiety may lead to overconsumption of energy, whereas diets with high protein content can enhance satiety. Developing diets that allow subjects to eat until hunger is satisfied but to sustain a negative energy balance is potentially a strong strategy. Key areas where more evidence is required include the attributes of diets that work best, the mechanisms underlying these effects, and their applicability across the life-course and in different subject groups. This evidence will be needed to better match dietary solutions to consumer needs. High-protein diets appear to be effective when fed *ad libitum* both in inducing weight loss^(20,21,45), and in preventing weight regain after weight loss⁽¹⁸⁾. In the latter study, a 26-week European, multicentre, intervention within the EU project, Diogenes, a diet with elevated protein content and reduced glycaemic index has emerged as an optimal for the prevention of weight regain. Additional studies are addressing the safety of high-protein diets⁽⁴⁶⁾, as well as their efficacy, and the mechanisms underlying their effects, where the gastrointestinal peptides, glucagon, glucagon-like peptide-1, and peptide YY₃₋₃₆, probably contribute to the satiety-stimulating effect⁽⁴⁷⁾.

The Scientific Opinion of EFSA in 2010⁽⁴⁸⁾ on health claims related to dietary protein with respect to increased satiety and reduction in energy intake leading to beneficial change in body weight was that for both an increase in satiety leading to a reduction in energy intake, and contribution to the maintenance or achievement of a normal body weight, a cause and effect relationship with dietary intake of protein had not been established.



Dietary fibre

Dietary fibre encompasses numerous diverse chemical structures with varying physicochemical properties (e.g. viscosity, solubility and fermentability) which can influence the magnitude of effects on appetite, energy intake and body weight⁽⁴⁹⁾. In general, foods high in fibre require more chewing, thereby allowing more time for release of satiety signals, can increase retention time in the stomach and small intestine due to bulking and increased viscosity, which may reduce energy density and prolong exposure of enteroendocrine cells to luminal contents, and, passing undigested through the upper gut, may be fermented by microorganisms in the large intestine to SCFA, which in turn may contribute to satiety through release of gut hormones. At an epidemiological level, a weak inverse association has been observed between total dietary fibre intake and bodyweight change⁽⁵⁰⁾. In the European Prospective Investigation of Cancer prospective cohort study examining participants from five European countries with a large variation in fibre intake followed for an average of 6.5 years, a 10 g/d higher total fibre intake was associated with -39 g/year weight change; fibre intake from cereals was more effective than that from fruit and vegetables. Systematic review of the relationship between the specific dietary fibre types and beneficial outcomes revealed that the more viscous fibres (pectins, β -glucans and guar gum) had a greater effect on subjective appetite and acute energy intake, although effect sizes on energy intake and body weight were small (reduction in body weight of 0.014 % per 4 weeks per gram increase of fibre intake across all fibre groups)⁽⁴⁹⁾. Key areas for future investigation were identified as assessment of the relevance of short-term effects, for example, appetite sensation, for longer-term energy intake and body weight, along with the requirement to establish the physicochemical properties of specific dietary fibres in much more detail. Such investigation might offer the prospect of amplifying the modest biological effects observed to date with relatively poorly characterised fibre groups⁽⁴⁹⁾.

The Scientific Opinion of EFSA in 2010⁽⁵¹⁾ on a range of health claims related to dietary fibre was that fibre was not sufficiently well characterised and that a cause and effect relationship between dietary fibre and the claimed effects had not been established.

A multi-disciplinary approach to diet change

The ambition of widespread dietary behaviour change as a third arm of an anti-obesity strategy to complement pharmacological and surgical interventions requires effective engagement and connectivity between the food and drink industry and public health interests. This will be necessary in order to deliver healthier food products without undermining sustainable economic development in this key sector. This engagement should be underpinned by a multi-disciplinary academic perspective. Combining healthier food, targeted behaviour change and socioeconomic reality with diet-relevant biological

processes requires a truly multi-disciplinary approach that brings together economists, psychologists, sociologists and social scientists, as well as a wide range of experts from different scientific disciplines. Such connectivity is apparent in the design of the strategic research programmes being brought forward by the Scottish Government and the European Commission, as detailed earlier. This should be the model for tackling overconsumption of energy and NCD if we are not to lose more time in translating findings between disciplines.

Conclusion

It is unlikely that food could be developed as a viable weapon in our armoury for tackling overconsumption of energy and metabolic disease without the active engagement of the food and drink industry in the reformulation process. Clearly, however, foods cannot be allowed to be marketed to the consumer under the cover of false or misleading health-related claims, and caution will always need to be exercised before such claims are granted. The widespread failure of claimants to receive a favourable health claim opinion from EFSA is indicative of applications in which either supporting evidence is inadequate or the supposed bioactive is not clearly defined, suggesting that the applicants need to aspire to a higher standard of evidence in order to achieve the desired outcome. Equally, to encourage innovation in the healthy food sector there does need to be a realistic prospect of claims being accepted, if we are not to stifle innovation in the food and drink industry, which will inevitably be the major engine bringing forward new products to support weight management. Achieving the correct balance here may be a challenge but serves to emphasise the need for the multi-disciplinary approach, advocated earlier. Of the present best candidates for deployment in reformulated foods, it may not be realistic to advocate high-protein diets as presently formulated for a substantial proportion of the population. More likely is a scenario where we try to harness the biological effect (protein-induced satiety) with carefully titrated formulations targeted at particular sectors of the population. This might involve more widespread use of protein sources of plant origin, or efficacious combinations of protein and fibre. Similarly, the effects of fibre alone may be rather small when applied non-specifically, but if harnessed correctly and in combination with other dietary components amplification of effect might be achievable. As already outlined, the target for reformulated food is more likely one of the slow progressive weight gain rather than tackling pre-existing obesity, although some interventions might also be effective here. This approach obviously resonates with the concept that there is no one-size-fits-all solution to weight management of the population in our present obesogenic environment.

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Conflicts of Interest

A. M. J. holds commercially funded grants and has acted as a consultant within the food industry sector. J. C. G. H. holds commercially funded grants and has acted as a consultant within the food industry sector, on behalf of the University of Liverpool.

Authorship

The concepts presented here are detailed as a collaboration between all authors. All authors have contributed to, seen and approved the manuscript.

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