REVIEW

Mycoprotein and health

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Summary

Mycoprotein is a high protein, high fibre, low fat food ingredient derived from fermentation of the filamentous fungus *Fusarium venenatum*. Interest in the putative role of mycoprotein in lowering blood cholesterol concentrations, reducing energy intakes and controlling blood sugar levels has generated a small number of human studies investigating the effects of mycoprotein on cholesterol reduction, satiety and insulinaemia/glycaemia.

In today's 'obesogenic' environment, in which there is an abundance of foods high in fat and/or sugar available to consumers, there is growing interest in foods that are both nutritious and satiating, but that are of low-energy density, and are low in saturates, salt and sugar. Mycoprotein has a favourable fatty acid profile (being relatively low in saturates), a fibre content that is comparable with other vegetarian protein sources, and a naturally low sodium content. Mycoprotein is a good source of zinc and selenium but the levels of iron and vitamin B12 in mycoprotein are low in comparison to red meat.

A small number of studies investigating the cholesterol-lowering effects of mycoprotein have been carried out among normo- and hypercholesterolaemic adults. The published studies to date have a number of limitations (including small sample sizes and short study durations), but overall the studies report statistically significant reductions in total cholesterol amongst hypercholesterolaemic subjects (in the order of 4–14%). These results look promising in terms of the ability of mycoprotein to contribute modest but meaningful effects on blood cholesterol concentrations, as part of a varied and balanced diet. However, the exact amount of mycoprotein that would need to be consumed in free-living populations to have meaningful effects on cholesterol is a candidate for further confirmatory research.

A number of studies have investigated the effects of mycoprotein in comparison with other protein sources on satiety. Several studies suggest that the effects of mycoprotein on satiety are greater than an equivalent amount of chicken but it is unclear what mechanism underlies this. The studies conducted so far are relatively small, and carried out under controlled conditions, so it is difficult to extrapolate the results to larger free-living populations.

The promotion of mycoprotein could potentially be useful, alongside other strategies, in the management of obesity and type 2 diabetes, as it appears to show beneficial effects on glycaemia and insulinaemia in the small number of studies where this has been investigated. More research is needed to better understand the

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mechanism of action whereby mycoprotein influences glycaemia and insulinaemia, and whether there is any dose-dependent effect.

This paper reviews the published evidence for mycoprotein and the topics above, draws interim conclusions about the role of mycoprotein in human health and identifies areas for future research.

Keywords: cholesterol, glycaemic response, mycoprotein, satiety, Quorn

Introduction

Current UK dietary guidelines promote the consumption of a diet based on cereals and fruits and vegetables, with moderate amounts of milk and dairy products; meat, fish, eggs and beans; and limited amounts of foods and drinks high in fat and/or sugar.

In today's 'obesogenic' environment, in which there is an abundance of foods high in fat and/or sugar available to consumers, there is growing interest in foods that are both nutritious and satiating, but that are of low-energy density, and are low in saturates, salt and sugar.

Mycoprotein is a high-protein, high-fibre, low-fat food ingredient derived from fermentation of the filamentous fungus *Fusarium venenatum*. Interest in the putative role of mycoprotein in lowering blood cholesterol concentrations, reducing energy intakes and controlling blood sugar levels has generated a small number of human studies on mycoprotein and cholesterol reduction, satiety and insulinaemia/glycaemia.

This paper aims to review the published evidence for mycoprotein and hypercholesterolaemia, satiety and insulinaemia/glycaemia, in order to draw interim conclusions about the role of mycoprotein in human health, and to identify areas for future research.

What is mycoprotein?

Mycoprotein is a food produced by continuous fermentation of the filamentous fungus *Fusarium venenatum*, on a carbohydrate substrate, to produce a high-protein, low-fat food ingredient. Mycoprotein can be textured and flavoured to resemble meat and is sold only under the trade name 'Quorn' (Marlow Foods, Stokesley, North Yorkshire, UK). Mycoprotein is the main protein ingredient in a variety of mycoprotein products available throughout Europe and the United States, including mince, chicken-style pieces, ready meals, pies and pasties.

Development of mycoprotein

During the 1960s and 1970s, nutritionists and politicians across the world were concerned that the predicted growth in the world's population would lead to global food and protein shortages in the future.

This led food scientists to begin searching for novel food sources that could help to meet the predicted increase in global demand for food and protein. Initially this search focussed upon single-cell proteins from bacteria and yeasts (Kihlberg 1972; Kharatyan 1978) but, in human feeding trials, many bacterial and yeast proteins were found to cause adverse side effects, including gastrointestinal symptoms, rashes and raised blood and urinary uric acid concentrations (Udall *et al*. 1984).

After several years of searching around the world for novel food sources, the focus of the search turned to filamentous microfungi that are commonly found in soil and, in 1967, an organism (*Fusarium venenatum*) was identified in a field in Marlow, Buckinghamshire, UK, which was eventually exploited to produce mycoprotein.

Research and development work continued for many years to assess the safety and nutritional value of mycoprotein (Udall *et al*. 1984) but it was not until the early 1980s that mycoprotein could be produced on a large enough scale to market it as a new protein food ingredient.

Production of mycoprotein

A detailed description of mycoprotein production is given by Edelman *et al*. (1983) and Edwards (1986). Mycoprotein is produced commercially by continuous flow fermentation of *Fusarium venenatum* on a glucose substrate (Edwards 1986). The fermentation of mycoprotein is carried out under aerobic, aseptic conditions in sterile fermentation tanks.

Fusarium venenatum is fed a continuous flow of nutrients (including vitamins and minerals to supply essential nutrients for growth), whilst a proportion of the culture broth is simultaneously removed to maintain a constant volume of fermentation medium. This replaces the total volume of broth in the fermenter every 5–6 hours.

After harvesting from the fermenter, the culture broth is subjected to a short heat-treatment process to reduce its ribonucleic acid (RNA) content, from 10% to less than 2% (dry weight), achieved by heat activation of the endogenous RNAse enzymes. This helps to minimise the content of purines that, if ingested in large amounts, can lead to an excess of uric acid in the body and increase the likelihood of gout.

The heat-treated culture broth is then centrifuged to remove much of the water, and the mycoprotein is then recovered as a paste. Finally, the mycoprotein is mixed with albumen from free-range chicken eggs, which acts as a binder, and textured and flavoured to resemble meat.

Safety of mycoprotein

Following a 10-year evaluation of its safety, mycoprotein was approved for use as a food in the UK by the Ministry of Agriculture, Fisheries and Food in 1983, followed by the issue of a certificate of free sale throughout the UK in 1985 (Solomons 1987; Edwards 1993). In January 1985 the first retail mycoprotein product, a savoury pie, was launched in the UK.

The tolerance and nutritional value of mycoprotein in human subjects was studied by Udall and colleagues in 1984 (Udall *et al.* 1984). In a double-blind, randomised, placebo-controlled, crossover design tolerance study, 50 males and 50 females were fed four cookies each containing 5 g mycoprotein (dry weight) per day, or control cookies, in addition to their usual diets. The study lasted 67 days, with a 7 day washout period between the mycoprotein and control periods. In total, participants consuming the mycoprotein cookies consumed 20 g of mycoprotein per day. During the study, participants were asked to keep personal diaries and record any unusual symptoms. Blood samples were obtained from the participants and concentrations of 17 serum constituents were measured, including glucose, blood urea nitrogen, sodium and potassium, uric acid, total protein and cholesterol.

Of the 100 participants who completed the tolerance study, none reported any gastrointestinal symptoms or skin rashes ascribable to consuming mycoprotein. Some minor complaints were recorded by several individuals but, as these were not mentioned to staff, the researchers judged these to be unrelated to mycoprotein consumption. No significant changes were observed in serum constituents, with the exception of serum total cholesterol. This decreased significantly during the 30-day mycoprotein period, from a mean baseline value of 4.87 mmol/l to 4.53 mmol/l at the end of the mycoprotein period ($P < 0.001$).

Udall and colleagues (1984) concluded that, at the level of intake tested, mycoprotein is safe for human consumption and that the likelihood of adverse reactions to it is no greater than with many other common foods (for example milk, peanuts, soya and eggs, which all contain allergenic proteins).

In 2002, mycoprotein was recognised by the United States' Food and Drug Administration (FDA) as 'Generally Recognized as Safe', and seven mycoprotein products were launched in the United States under the trade name Quorn.

Mycoprotein products are deemed to be safe for consumption by children and babies but, because of the high energy requirements of rapidly growing children and the relatively low energy density of mycoprotein and its high fibre content, mycoprotein products are not recommend for children under three years old.

Nutritional aspects of mycoprotein

Mycoprotein is a high-protein, high-fibre, low-fat food ingredient that is suitable for inclusion in a healthy diet. A small number of experimental studies have suggested a range of potential health benefits of mycoprotein, including lowering blood cholesterol concentrations, enhancing satiety (and so potentially reducing energy intakes), and helping to control blood sugar levels (which is useful in the management of obesity and type-2 diabetes). The nutritional content of mycoprotein in its food ingredient form is shown in Table 1.

Mycoprotein is the main ingredient in a variety of Quorn products available throughout Europe and the United States, including meat style pieces, fillets, cold-cut style slices, nuggets, burgers, sausages, ready meals, pasties and pies (see Marlow Foods 2008 for a complete list of products available in the UK). All Quorn products are suitable for vegetarians, but not vegans, because of the use of egg albumin as a binder.

Quorn products are widely consumed in Europe, with 23 million European consumers reporting purchase of Quorn products in 2001, and over 500 000 Quorn meals eaten every day in the UK (Premier Foods 2008, Personal Communication).

Mycoprotein has a favourable fatty acid profile, being relatively low in saturates, and has a fibre content that is comparable with other vegetarian protein sources. It is also naturally low in sodium. Table 2 provides a comparison between mycoprotein and other protein sources with respect to their nutrient composition, which reflects these positive attributes. However, the levels of iron and vitamin B12 in mycoprotein are low in comparison with red meat and the iron will be less bioavailable, as it is present as non-haem iron. Mycoprotein is a good source of zinc (9.0 mg per 100 g wet weight mycoprotein) and selenium (20 μg selenium per 100 g wet weight mycoprotein). Table 3 summarises the nutritional content of the key Quorn products consumed in the UK, together with their typical mycoprotein 'dose' per meal (dry weight mycoprotein).

Under the current European Regulation on Nutrition and Health Claims (European Commission 2007) the claim 'low fat' can be made on Quorn products containing less than 3 g of fat per 100 g. The claim 'contains fibre' can be made on Quorn products containing at least 3 g of fibre per 100 g and the claim 'high in fibre' can be made on products containing over 6 g of fibre per 100 g.

Table 1 Nutritional composition of mycoprotein per 100 g (wet weight)

Nutrient	Quantity
Energy (kJ)	360
Energy (kcal)	86
Protein (g)	11.5
Total carbohydrate (g)	1.7
of which sugars	0.8
Total fat (g)	2.9
of which saturates	0.6
of which monounsaturates	0.5
of which polyunsaturates	1.8
Dietary fibre (NSP) (g)	6.0
Sodium (mg)	4.0

Source: Marlow Foods (2008).
NSP, non-starch polysaccharides.

Mycoprotein and health

Interest in the putative role of mycoprotein in lowering blood cholesterol concentrations, reducing energy intakes and controlling blood sugar levels has generated a small number of human studies on the effects of mycoprotein on hypercholesterolaemia, satiety and insulinaemia/glycaemia.

Diet and cardiovascular disease (CVD)

CVD, which includes coronary heart disease (CHD) and stroke, is the leading cause of death and ill health globally. Nearly half of all deaths in Europe (49%) are caused by CVD (Petersen *et al*. 2005) and important diet-related risk factors for CVD include high blood

Table 2 Nutritional composition of meat alternatives and meat per 100 g

Food	Energy kJ	Energy kcal	Protein (g)	Total carbohydrate (g)	Total fat (g)	Saturates (g)	Fibre (NSP) (g)	Sodium (mg)	Iron (mg)	Zinc (mg)	Vitamin B12 (μg)	Selenium (μg)
Mycoprotein food ingredient (wet weight basis)	360	86	11.5	1.7	2.9	0.6	6.0	4	0.5	9.0	0	20
Tofu, steamed	304	73	8.1	0.7	4.2	0.5	Unknown	4	1.2	0.7	0	Unknown
Soya beans, dried, boiled in unsalted water	590	141	14.0	5.1	7.3	0.9	6.1	1	3.0	0.9	0	5
Red kidney beans, dried, boiled in unsalted water	440	103	8.4	17.4	0.5	0.1	6.7	2	2.5	1.0	0	6
Hazelnuts	2685	650	14.1	6.0	63.5	4.7	6.5	6	3.2	2.1	0	2
Eggs, raw	627	151	12.5	Trace	11.2	3.2	0	140	1.9	1.3	2.5	11
Milk, semi-skimmed, average	195	46	3.4	4.7	1.7	1.1	0	43	0.02	0.4	0.4	1
Lean beef, average, raw	542	129	22.5	0	4.3	1.7	0	63	2.7	4.1	2	7
Lean lamb, average, raw	639	153	20.2	0	8.0	3.5	0	70	1.4	3.3	2	4
Lean pork, average, raw	519	123	21.8	0	4.0	1.4	0	63	0.7	2.1	1	13
Chicken, light meat, average, raw	449	106	24.0	0	1.1	0.3	0	60	0.5	0.7	Trace	12

Source: Food Standards Agency (2002); Marlow Foods (2008).
N/A, data not available; NSP, non-starch polysaccharides.

Table 3 Nutritional composition of selected Quorn products and their mycoprotein 'dose'

Food	Typical portion size	Nutrient per portion										
		Typical mycoprotein 'dose' per meal (dry weight mycoprotein) (g)	Energy		Protein (g)	Carbohydrate (g)	Of which sugars (g)	Total fat (g)	Of which saturates (g)	Fibre AOAC (g)	Sodium (g)	Salt equivalent (g)
			kJ	kcal								
Quorn mince	100 g	21	397	94	14.5	4.5	0.6	2	0.5	5.5	0.1	0.3
Quorn pieces (chicken style)	100 g	21	433	103	14	5.8	1.3	2.6	0.6	5.5	0.4	1.0
Quorn sausages	150 g (3×50 g sausages)	12	711	171	22.5	7.5	0.6	5.7	0.9	5.1	0.6	1.5
Quorn deli slices (chicken style)	50 g (half a pack)	9	227	54	8.2	2.3	0.6	1.3	0.4	3	0.3	0.8
Quorn breaded poppin bites	125 g (half a pack)	19	992	238	13.8	18.8	1.9	11.9	2.5	3.1	0.6	1.5
Quorn cottage pie	250 g (half a 500 g pie)	4	618	148	6.25	22.5	2	3.5	2.3	6.5	1.0	2.5
Quorn quarter pounder	114 g (one-quarter pounder)	9	720	171	20.4	10.2	2	5.4	0.7	3.4	0.7	1.8
Quorn cornish style pasty	150 g (one pasty)	4	1667	399	8.3	37.5	0.8	24	10.5	4.5	0.5	1.3

Source: Marlow Foods (2008).
Data for Quorn products is as sold.
AOAC, Association of Official Analytical Chemists.

cholesterol concentration, obesity, high blood pressure and type-2 diabetes (Stanner 2005).

It has been recognised for some time that people consuming plant foods that are high in fibre and low in fat (particularly saturates) are at reduced risk of developing chronic diseases, including CHD and stroke (see Denny & Buttriss 2007).

Such a diet plays a key role in helping to lower blood cholesterol concentration and, recently, particular attention has been paid to the role that specific plant components, including plant proteins, fibre and plant stanols and sterols, can have in lowering blood cholesterol concentrations (Goldberg 2003; BNF 2008). Similar to many plant foods, mycoprotein is a source of protein, is high in fibre and is low in total fat and saturates.

Plant proteins, in particular soya protein, have been shown to have a beneficial effect on health, lowering 'bad' low-density lipoprotein (LDL) cholesterol concentrations and, sometimes, raising 'good' high-density (HDL) lipoprotein cholesterol concentrations (Anthony *et al.* 1996; Taku *et al.* 2007).

Anderson *et al.* (1995) carried out a meta-analysis of 38 human studies on the effects of soy protein intake on serum lipid profiles, concluding that soy protein (an average of 47 g per day) significantly decreased total and LDL cholesterol concentrations by 9.3% and 12.9%, respectively. On the basis of this evidence and further clinical studies, the FDA approved a health claim in the United States for cholesterol reduction, based on an intake of 25 g of soya protein per day. A similar claim was approved in the UK by the Joint Health Claims Initiative, a voluntary initiative that has now been superseded by the EU Regulation on Nutrition and Health Claims made on foods mentioned earlier. The mechanism of action of soya protein remains unclear but isoflavones are thought to play a role in lowering plasma LDL cholesterol (see Cassidy *et al.* 2006).

Dietary fibre has also been shown to reduce cholesterol concentrations (see Lunn & Buttriss 2007). Viscous fibres in the diet, particularly those from fruits and grains, such as guar gum, pectin, beta-glucans and psyllium fibre, can lower blood cholesterol concentrations by reducing the amount of cholesterol absorbed from the small intestine (Lia *et al.* 1997) and the amount of bile acids absorbed in the ileum (Lia *et al.* 1995). Synthesis of LDL cholesterol in the liver may also be inhibited by the production of short chain fatty acids (namely propionic acid) in the colon, as a result of bacterial fermentation of dietary fibre in the large bowel (Hara *et al.* 1999). This may be of relevance to mycoprotein because it has a high fibre content (6.0 g per 100 g wet weight mycoprotein), attributable to its cell wall component, approximately one-third of which is chitin (n-acetyl glucosamine) and two-thirds beta-glucan.

Studies investigating the cholesterol-lowering effects of mycoprotein

Turnbull *et al*. (1990) carried out a 3-week non-blinded, randomised controlled metabolic study investigating the effects of consuming mycoprotein daily on the cholesterol levels of 17 healthy adults with a baseline total cholesterol concentration of 5.2–6.2 mmol/l. Subjects were free-living but all meals were consumed under supervision in a metabolic unit, with subjects in the intervention group ($n = 9$) consuming on average 191 g mycoprotein per day (47.8 g dry weight) distributed over lunch and dinner for 3 weeks, in place of meat. Mycoprotein was consumed as commercially available pies, breadcrumb-coated pieces or dishes containing mycoprotein chunks. Subjects in the control group consumed equicaloric quantities of meat and meat products.

The authors of the study reported a 13% reduction over the 3-week period in plasma cholesterol in the intervention group ($P < 0.01$), a 9% reduction in LDL cholesterol ($P < 0.01$) and a 12% increase in HDL cholesterol ($P < 0.001$), compared with a 12% increase in LDL cholesterol in the control group and an 11% decrease in HDL cholesterol. When comparing the intervention group with the control group, the overall reduction in total cholesterol was 14.3% (Table 4). Mycoprotein was well tolerated in the study, with subjects reporting minimal side effects (mainly flatulence, which ceased after a few days).

Although this study was small and only 3 weeks long, the dietary intake of the study participants was well controlled. There were no major differences in mean nutrient intakes between the intervention and the control group (except for an intended 29% increase in dietary fibre in the intervention group), and the fatty acid content of the two diets was closely balanced. The results of the study therefore point to a beneficial effect of the dietary fibre component of mycoprotein on blood lipids, as the only major difference between the mycoprotein and control diets was that the mycoprotein diet contained 11.2 g per day more dietary fibre than the control diet.

In a follow up to this study, the same group of researchers investigated the effects of mycoprotein on blood lipid profiles of free-living subjects consuming their habitual diets, supplemented with mycoprotein (Turnbull *et al*. 1992). In this single-blind, randomised placebo-controlled study, 21 subjects with a baseline total cholesterol concentration of >5.2 mmol/l were allocated to a diet supplemented with either mycoprotein-containing cookies or control cookies.

Subjects in the intervention group consumed the equivalent of 130 g mycoprotein (wet weight) per day (26.9 g dry weight), in cookies for 8 weeks. In this group ($n = 11$), total blood cholesterol concentrations fell by 15.9% on average ($P < 0.05$) during the 8 weeks of the study; the reduction in cholesterol was most pronounced during the first 4 weeks of the study. An 8% reduction in total cholesterol was also seen in the control group during the first 4 weeks of the study, giving an overall reduction in total cholesterol of 8.2% when comparing the intervention group with the control group (Table 4).

No significant changes in HDL cholesterol concentrations were observed in the study but LDL cholesterol decreased by 21.5% in the intervention group, compared with an 8.9% reduction in the control group, giving an overall reduction in LDL cholesterol of 12.8% when comparing the intervention group with the control group (Table 4).

This follow-up study was longer than the metabolic study (8 weeks *vs*. 3 weeks) but, as subjects were free-living, there was less control over subjects' diets (monitored using three weighed 5-day dietary records). Despite subjects consuming their habitual diet, the results correlate well with the results of the metabolic study, save for the significant increase in HDL cholesterol observed in the metabolic study, which was not observed in this study.

The average fibre intakes of the intervention group (26.0 ± 4.6 g per day) and control group (25.0 ± 6.2 g per day) in this study were very similar (unlike in the metabolic study); the authors hypothesise therefore that it could be the type of dietary fibre found in mycoprotein that is responsible for the observed effects, rather than the quantity of dietary fibre in the mycoprotein diet exceeding that of the control diet. The fibre content of mycoprotein (25% of dry matter) is attributable to its cell wall component, approximately one-third of which is chitin and two-thirds beta-glucan (Turnbull *et al*. 1990). The total fat intake of the mycoprotein and control groups was very similar, and so it is unlikely to explain the observed reductions in total and LDL cholesterol.

The effect of mycoprotein on serum lipid profiles in a Japanese population has also been investigated. Ishikawa (1995) recruited 37 hypercholesterolaemic subjects to a double-blind, randomised placebo-controlled study. Eleven subjects were randomised to a diet supplemented with cookies containing 24 g (dry weight) mycoprotein and 14 subjects were randomised to a diet supplemented with cookies containing 12 g (dry weight) mycoprotein, both for 4 weeks. In both

Table 4 Studies investigating the cholesterol-lowering effects of mycoprotein

Author (year)	Study type	Country of research	Number of subjects: No. of subjects included in analyses	Number of subjects: No. of subjects in Intervention group	Age (years)	Study population	Baseline total cholesterol concentration (mmol/l): Intervention group	Baseline total cholesterol concentration (mmol/l): Control group	Intervention: Intervention	Intervention: Average amount of mycoprotein per day	Intervention: Duration of diet	Change in cholesterol from baseline (mmol/l): Intervention group	Change in cholesterol from baseline (mmol/l): Control group	Change in cholesterol from baseline (mmol/l): Overall change (Intervention compared with Control)
Turnbull *et al.* (1990)	Non-blinded randomised controlled metabolic study	UK	17	9	19–48	Healthy adults with total cholesterol between 5.2–6.2 mmol/l drawn from a university population, BMI 16.9–32.1 kg/m^2. Subjects free-living but all meals consumed under supervision	5.54 ± 0.47	5.31 ± 0.27	Intervention group fed mycoprotein at lunch & dinner in place of meat for 3 weeks	47.8 g dry weight (191 g wet weight)	3 weeks	Final value 4.81 ± 0.45 Change = –0.74 mmol/l (significantly different from control $P < 0.01$)	Final value 5.37 ± 0.52 Change = +0.05 mmol/l	Change = –0.79 **(14.3% reduction)**
Turnbull *et al.* (1992)	Single-blind randomised placebo-controlled study	UK	21	11	25–61	Free-living healthy adults with total cholesterol > 5.2 mmol/l drawn from a university population, BMI 21.3–33.0 kg/m^2	5.97 ± 0.61	5.75 ± 0.96	Subjects allocated to diet supplemented with mycoprotein cookies or soya protein cookies	26.9 g dry weight (107.6 g wet weight)	8 weeks	Final value 5.02 ± 0.46 Change = –0.95 mmol/l (significantly different from control $P < 0.05$)	Final value 5.29 ± 1.25 Change = –0.46 mmol/l	Change = –0.49 **(8.2% reduction)**
Ishikawa (1995)	Double-blind randomised placebo-controlled study	Japan	37	24 g mycoprotein group: 11 12 g mycoprotein group: 14	30–70	Japanese patients undergoing treatment for hypercholesterolaemia at medical centres. Subjects selected on basis of total cholesterol > 220 mg/dl but 15 subjects reported to have a total cholesterol of <220 mg/dl pre-study	Unknown	Unknown	Subjects allocated to diet supplemented with cookies containing total amount of 12 g or 24 g mycoprotein, or placebo cookies	24 g dry weight (96 g wet weight) 12 g dry weight (48 g wet weight)	4 weeks	Unknown	Unknown	Significant reduction from baseline
Udall *et al.* (1984)	Double-blind randomised placebo-controlled crossover tolerance study	United States	100	50 + 50 (crossover)	18–59	Free-living healthy subjects living in the US. Cookies consumed under supervision 5 d/week & ration given for weekend	4.87		Subjects allocated to diet supplemented with mycoprotein cookies or control cookies	20 g dry weight (80 g wet weight)	30 days with 7 day washout period between diets	Final value 4.53 Change = –0.34 mmol/l (significantly different from baseline $P < 0.001$)		Change = –0.34 mmol/l **(7.0% reduction from baseline)**
Nakamura *et al.* (1994)	Randomised, non-controlled intervention study	Japan	15	24 g mycoprotein group: 7 18 g mycoprotein group: 8	25–60	Free-living healthy male Japanese subjects	24 g group: 4.87 18 g group: 4.62		Subjects allocated to diet supplemented with cookies/crisps containing a total amount of 24 g or 18 g of mycoprotein (dry weight)	24 g dry weight (96 g wet weight) 18 g dry weight (72 g wet weight)	8 weeks	Final value 24 g group: 4.66 Change = –0.21 mmol/l (*ns*) 18 g group: 4.65 Change = +0.03 mmol/l (*ns*)		24 g group Change = –0.21 mmol/l **(4.3% reduction from baseline** (*ns*)**)**
Homma *et al.* (1995)	Randomised crossover intervention study	Japan	52	24 g mycoprotein group: 26 18 g mycoprotein group: 26	30–69	Free-living healthy male Japanese subjects. Within 24 g group, 13 subjects had plasma total cholesterol > 5.7 mmol/l. Within 18 g group, 14 subjects had plasma total cholesterol > 5.7 mmol/l	24 g group: unknown 18 g group: unknown		Subjects allocated to diet supplemented with crisps containing mycoprotein	24 g dry weight (96 g wet weight) 18 g dry weight (72 g wet weight)	4 weeks with 8 week washout period between diets	24 g group: 6.7% reduction from baseline (significantly different from baseline $P < 0.01$) 18 g group: 1.6% reduction from baseline (*ns*)		24 g group: **6.7% reduction from baseline** ($P < 0.01$)

BMI, body mass index; *ns*, not significant.

the 12 g and 24 g mycoprotein groups, significant reductions from baseline were observed for both total and LDL cholesterol, with results suggesting a dose-dependent response.

However, another Japanese study conducted by Nakamura (1994) failed to show a change in total cholesterol concentrations of healthy Japanese subjects consuming 18 g (dry weight) mycoprotein per day. But the study did demonstrate a significant effect among subjects consuming 24 g mycoprotein per day, when the analysis included only those subjects with a baseline cholesterol concentration of >4.9 mmol/l. The study was a randomised intervention trial, without a control group, and the 15 subjects consumed mycoprotein as either cookies or savoury snack 'chips' for 8 weeks.

In a larger crossover study among 32 healthy free-living Japanese subjects (Homma *et al*. 1995), a 9.7% decrease in total cholesterol was observed among subjects consuming 24 g (dry weight) mycoprotein per day as savoury snack 'chips' ($P < 0.01$), but only when the analysis included only those subjects with a total cholesterol concentration of >5.7 mmol/l. A non-significant 0.7% decrease in total cholesterol concentration was observed among subjects with a total cholesterol concentration of >5.7 mmol/l consuming 18 g (dry weight) mycoprotein per day. For all subjects consuming 24 g mycoprotein per day, a statistically significant 6.7% reduction in total cholesterol was observed, but for subjects consuming 18 g mycoprotein per day, the reduction in total cholesterol (1.6%) was not significant. These results suggest a dose-dependent effect.

Overall, in spite of the limitations of the published studies on mycoprotein and cholesterol lowering (for example the small sample sizes, short study lengths and the fact that, in some of the studies, all subjects have been analysed together rather than looking at normo- and hypercholesterolaemic subjects separately), the effects seen for cholesterol are all in the same direction (reductions are seen in total and LDL cholesterol) and, according to the papers, the effects were statistically significant among hypercholesterolaemic subjects.

An important consideration in assessing the effect of mycoprotein on blood lipid profiles is that there appears to be a dose-dependent relationship. A reduction in cholesterol concentration is seen at intakes of mycoprotein varying from 20–48 g (dry weight) mycoprotein per day (80–192 g wet weight mycoprotein per day), although in two studies (Nakamura *et al*. 1994; Homma *et al*. 1995), an effect is seen with 24 g (dry weight) mycoprotein per day but not with 18 g (dry weight) mycoprotein per day.

These results therefore look promising in terms of the feasibility of consumers achieving a sufficient daily intake of mycoprotein to produce meaningful effects on blood cholesterol concentrations, and in terms of opportunities for new product development (NPD).

The maximum cholesterol-lowering effect achieved in research (a reduction of 14.3%; Turnbull *et al*. 1990) was seen at an intake of 48 g (dry weight) mycoprotein per day, but a more modest reduction (in the region of 10%; a reduction considered to be physiologically meaningful) could be expected to be seen at intakes of around 30–35 g (dry weight) mycoprotein per day based on the studies published to date (see Table 4).

The exact amount of mycoprotein and regularity with which it needs to be consumed to have the effect on cholesterol observed in the studies, summarised in Table 4, is a clear candidate for confirmatory research. This opens up opportunities for NPD as product development could be targeted towards producing foods that contain physiologically meaningful levels of mycoprotein, and identifying achievable and practical ways of incorporating mycoprotein-containing foods in the diet.

At present mycoprotein offers the potential to complement other existing dietary strategies to lower cholesterol. For example, substantial evidence exists that modifying dietary fatty acid intake in favour of mono- and polyunsaturates has beneficial effects on blood cholesterol (typically resulting in a 10% reduction in total and LDL cholesterol; see Buttriss 2005) and there is good evidence for an effect in consuming 2–3 g of plant sterols or stanols per day on LDL cholesterol concentrations (resulting in a 5–15% reduction in LDL cholesterol; see BNF 2008) and for an effect of consuming 25 g soya protein per day on total cholesterol concentrations (typically resulting in a 10% reduction in total cholesterol; see JHCI 2002).

Mycoprotein and satiety

Satiety is the sensation of being satisfied after consuming a food or drink. It persists for a period of time after consumption, until hunger returns and another eating occasion is initiated. This is distinct from satiation, the process that leads to stopping consumption, for example, ending a meal. The length of time that satiety persists potentially affects how long a person will go without food, and also how much they consume at a subsequent meal. Thus satiety is of great importance for weight control, as it can affect energy intake.

Satiety is initiated by the presence of nutrients in the gut and is also affected by signals indicating how much

fat is stored in the body, for example, the blood concentration of leptin that is released in proportion to adiposity and acts on brain centres to reduce appetite. For a review of the factors involved in satiety signalling see Wynne *et al.* (2005).

A great deal of research has been conducted on the effect of various foods, drinks or nutrients on satiety, and much of this has indicated that there is a hierarchy of satiating efficiency within the macronutrients, with protein being the most satiating, followed by carbohydrate, followed by fat (Blundell & Stubbs 1998). A number of studies have shown protein-rich test meals to be more satiating than carbohydrate- and fat-rich meals (Westerterp-Plantenga *et al.* 2007). However, the mechanism by which this increased satiety is mediated is not yet clear.

Some high-fibre foods and types of dietary fibre have also been shown to influence satiation and to have a strong satiating effect. It appears that the bulking properties of fibre affect satiation by increasing chewing time, and increasing gastric distension. Fibre also lowers the energy density of the diet.

Viscous fibres may enhance satiety by prolonging the intestinal phase of digestion and absorption of nutrients. This means that macronutrients have a longer period of time in which to interact with pathways producing satiety signals that tell the brain that enough food has been consumed (Slavin & Green 2007). Given that mycoprotein is high in both fibre and protein (see Table 1), it is plausible that it may have the potential to enhance satiety.

A number of studies have investigated the effect of mycoprotein on satiety, compared with other protein sources, generally chicken. They have all used the preload paradigm, whereby the food in question or a control food is given as a preload, then satiety is measured by monitoring self-reported changes in appetite and energy intake at subsequent meals. Generally this is done over the course of a day in a laboratory setting, where the environment and food consumption are carefully controlled. This may be repeated over a period of days and subjects may record food intake and/or ratings of appetite over a time period following the experiment to monitor any further changes.

Burley *et al.* (1993) investigated the effects of mycoprotein versus chicken on satiety in 18 lean healthy male and female subjects. The two lunches were matched for energy and protein content, but the mycoprotein meal was higher in fibre (11 g compared with 3 g in the chicken meal). Subjects consumed the test lunch, then an *ad libitum* meal in the evening. The study had a crossover design, so that all subjects completed two study days, one each for the mycoprotein and chicken test meals. Energy intake at the evening meal was reduced by 18% following the mycoprotein meal compared with the chicken meal. Self-reported food intake indicated that, although there was no further reduction of energy intake in the following 36 hours, subjects failed to compensate for the decreased energy intakes by consuming more. The authors speculated that, compared with previous studies they had performed with high-fibre foods (Burley & Blundell 1990; Burley *et al.* 1992), mycoprotein appeared to have a greater satiating power than other foods with a similar fibre content, and the specific types of fibre present in mycoprotein might have strong effects on satiety (Burley *et al.* 1993).

Turnbull *et al.* (1993) conducted a similar study in 13 lean healthy female subjects, also using a crossover design. Subjects were given either a chicken or mycoprotein test lunch. Ratings of appetite were taken just before the test meal and at intervals for 3 hours following. Palatability of the two meals was also measured and the ratings did not vary significantly between the mycoprotein and chicken lunches. Energy intake was recorded by subjects using a weighed food diary for the days before, during and after the study. According to the information from the food diaries, energy intake was reduced by 24% and 16.5% on the day of the study and the following day, respectively, after eating the mycoprotein lunch compared with the chicken lunch. Measures of subjects' desire to eat and prospective food consumption were also reduced when measured 3 hours after the mycoprotein *vs.* the chicken lunch. Again, the authors suggested that mycoprotein fibre seemed to be particularly satiating compared with the findings of studies using foods with comparable fibre contents. They concluded that either the fibre in mycoprotein is particularly satiating or that there is another component of mycoprotein responsible for this satiating effect (Turnbull *et al.* 1993).

Williamson *et al.* (2006) investigated the relative satiating qualities of mycoprotein, tofu (derived from soya) and chicken in 42 overweight adult female subjects. Subjects came to the laboratory fasted and consumed a standard breakfast. Four hours later a pasta preload made with either mycoprotein, tofu or chicken was given. These were matched for energy, protein and palatability but the mycoprotein preload was higher in fibre. Subjects acted as their own control and so came to the laboratory three times (with at least 1 day in between) to have all three preloads. Twenty minutes after the pasta preload, subjects were given a test lunch of sandwiches and instructed to eat as much or as little as they liked. The amount eaten was measured using a universal eating monitor (Kissileff *et al.* 1980) that

consists of a weighing scale concealed under a table cloth, connected to a computer that records the exact weight of food eaten over time. Four and a half hours after the test lunch, subjects were given a selection of foods to eat as an *ad libitum* dinner, and the amount of each food consumed was recorded to measure energy intake. Ratings of appetite were taken before and after the three meals and preload, and at intervals following the test lunch. Energy intake at the test lunch was reduced following both the tofu and mycoprotein preloads, compared with the chicken preload. There was no significant difference in this reduction in energy intake between the tofu and mycoprotein preloads. There were no significant differences between any of the three preloads for the ratings of appetite, or energy intake at the evening meal. However, this did mean that subjects did not compensate for eating less at lunchtime, after the tofu or mycoprotein preloads, by eating more at the evening meal (Williamson *et al*. 2006).

Thus, although several small studies suggest that the effects of mycoprotein on satiety are greater than an equivalent amount of chicken, it is unclear what mechanism underlies this. The fibre in mycoprotein is one-third chitin and two-thirds beta-glucan (Turnbull *et al*. 1991), neither of which are found in large amounts in most diets (oat-rich diets do provide beta-glucans, but these are characterised by β 1–4 linkages, whereas the beta-glucans in mycoprotein are characterised by β 1–3 and β 1–6 linkages). It is possible that the specific fibres found in mycoprotein might have a particular effect on satiety as mentioned earlier. Although it is plausible that a higher fibre food might be more satiating, the study by Williamson *et al*. (2006) raised questions about the validity of this hypothesis, given that the tofu preload, which had a similar fibre content to the chicken preload, was found to have the same satiating effect as mycoprotein.

There is currently inconsistent evidence for a difference in the effects on satiety of different protein sources in humans (Harvey-Anderson & Moore 2003). But it is possible that the protein from mycoprotein *vs*. that from chicken has a different effect on satiety.

The studies conducted so far on mycoprotein and satiety are relatively small and carried out under controlled conditions. Therefore it is difficult to extrapolate the results to larger free-living populations. The published studies have also been short-term so that any learned effects that would be relevant in the longer term will not have been observed. However, the effect of mycoprotein on satiety warrants further investigation and longer-term, larger studies are needed to confirm the results of the experiments that have been published to date.

Mycoprotein and glycaemic response

When carbohydrates are broken down, glucose is absorbed into the blood stream resulting in an increased concentration in the blood. In response to this, insulin is released from the pancreas sending a signal to the body tissues to increase their uptake of glucose. This results in a fall in blood glucose concentration. A number of factors influence the rate and duration of the glycaemic response. These include: the types of sugars that form the carbohydrate; the nature and the form of the starch as some are more digestible than others; the cooking and processing methods used; and the other nutrients in the food, such as fat or protein (see Alfenas & Matteso 2005).

Mycoprotein might be useful in the management of obesity and type-2 diabetes as it appears to show beneficial effects on glycaemia and insulinaemia (see below for further discussion). By decreasing the rate of glucose absorption, the amount of insulin secreted by the pancreas is reduced, lessening the impact of the 'insulin peak'. Periodic high peaks of insulin secretion are thought to contribute to the development of type-2 diabetes and heart disease, so a reduced or dampened glycaemic response is desirable (see Bornet *et al*. 2007; Venn & Green 2007). The exact mechanisms by which mycoprotein reduces the rise in postprandial blood glucose and insulin concentrations are unknown, but are thought to be associated with its high fibre content (6 g per 100 g wet weight). Fibre reduces the rate of gastric emptying, delaying the passage of food into the small intestine (Leclère *et al*. 1994). As a result, the glucose is absorbed more slowly. Additionally, the presence of soluble, viscous fibre slows the diffusion of glucose across the small intestinal wall, bringing about an improved glycaemic response (Edwards *et al*. 1988). Mycoprotein contains mainly beta-glucans and chitin that are partially soluble. However, it has been proposed that the chitin can undergo deacetylation to form a more soluble compound called chitosan, adding to the soluble proportion of fibre in the food (Turnbull & Ward 1995). Nevertheless, mycoprotein has a low carbohydrate content, so it is unlikely that the delayed breakdown and absorption of its carbohydrate, alone, would result in the observed improvements in the glycaemic response. Instead, it is more likely to be the effect that it has on the digestion of carbohydrate present in the food ingredients eaten at the same meal occasion that is bringing about the proposed benefit.

Interest in the anti-glycaemic effect of mycoprotein was sparked by an early observation by researchers Turnbull and Ward (1995). Using the World Health Organization protocol for an oral glucose tolerance test,

they investigated the glycaemic response in 19 healthy subjects. The study had a randomised crossover design, with each subject receiving either a test meal (20 g mycoprotein, dry weight) or control meal, in random order, with a 7-day washout period between the two meals. They observed that the serum glucose response was lower throughout the entire 120 minute postprandial period following the mycoprotein meal compared with the control. The insulin response was also lower. The only nutritional difference between the test and control meals was the dietary fibre content (the mycoprotein meal contained 11.2 g more dietary fibre). So the authors suggested that it is the viscous polysaccharides (fibre) that are reducing postprandial glycaemia and insulinaemia. More recently, Marks *et al.* have demonstrated a significant decrease in postprandial blood concentrations of insulin when 22.5 g mycoprotein (dry weight) was consumed in a test meal (Marks *et al.* 2004a). However, in this instance, no significant differences in postprandial glucose concentrations were reported; the glucose response was attenuated, but not significantly so. Other, as yet unpublished data, suggest that mycoprotein has an effect on improving glycaemic control in patients with type-2 diabetes, most probably by delaying the rate of carbohydrate absorption from the gut (Barnes, personal communication). Additionally, in a small-scale *in vitro* study designed to better understand the mechanisms by which mycoprotein brings about improvements in the glycaemic response, Marks *et al.* have demonstrated a significant 20% reduction in the rate at which glucose diffuses across a dialysis membrane, again relating this effect to the form of the fibre in the food (Marks *et al.* 2004b).

In summary, mycoprotein might be useful in the management of obesity and type-2 diabetes as it appears to show beneficial effects on glycaemia and insulinaemia. However, more research is needed to better understand the mechanism of action and whether there is any dose-dependent effect.

Conclusions

Mycoprotein is a high-protein, high-fibre, low-fat food ingredient that is suitable for inclusion in a healthy diet. A small number of experimental studies have suggested a range of potential health benefits of mycoprotein, including lowering blood cholesterol concentrations, enhancing satiety and helping to control blood sugar levels (which is useful in the management of obesity and type-2 diabetes).

The published studies on mycoprotein and hypercholesterolaemia have some limitations (for example, small sample sizes and short study durations), but statistically significant reductions (in the order of 4% to 14%) are seen in total cholesterol. These results look promising in terms of the ability of mycoprotein to contribute modest but meaningful effects on blood cholesterol concentrations as part of a varied and balanced diet. The exact amount of mycoprotein that would need to be consumed in free living populations, in order to have the effect on cholesterol observed in experimental studies, is a hot topic for further research. Following on from this, it would also be important to establish the most appropriate and practical food vehicles that are compliant with healthy eating recommendations.

Studies conducted on the effect of mycoprotein on satiety are relatively small and have been carried out under controlled conditions, making it difficult to extrapolate results from these studies to larger free-living populations. Further investigation is warranted with longer-term, larger studies to confirm the results of research published to date.

Mycoprotein could potentially be useful, alongside other strategies, in the management of obesity and type-2 diabetes, as it appears to show beneficial effects on glycaemia and insulinaemia. But more research is needed to better understand the mechanism of action whereby mycoprotein influences glycaemia and insulinaemia, and whether there is any dose-dependent effect.

As a high-fibre, low-fat food ingredient, consumption of mycoprotein is in keeping with current dietary guidelines, as part of a varied and balanced diet. Further research into the potential health benefits of mycoprotein is warranted, and this may open up exciting opportunities for product development targeted towards foods that contain physiologically meaningful levels of mycoprotein in a format that is consistent with healthy eating guidelines.

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