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THE NATURE, SOURCES, IMPORTANCE AND USES OF CEREAL DIETARY FIBRE

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by

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CONTENTS

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1. ABSTRACT

1.1 INTRODUCTION

Dietary fibre is a food component, the increased consumption of which is being advised by many on the grounds of its beneficial effects to health. This review provides definitions of what dietary fibre is; discusses the role of cereals as sources of dietary fibre, describes the effects of dietary fibre on human health, the implications for sales and suggests future areas of research.

1.2 NATURE AND SOURCES

Dietary fibre is a collective noun applied to plant materials of diverse chemical structure which share the common characteristic of being resistant to digestive enzymes produced by the alimentary canal. Dietary fibre can be subdivided into two chemical groups: carbohydrates (resistant starch and nonstarch polysaccharides - NSP) and lignins. Currently two methods of analysis are favoured by regulatory bodies for fibre analysis: a gravimetric method approved by the AOAC and used in Switzerland, USA and the Nordic countries and a chemical method measuring fibre as NSP (approved for use in the UK). Cereals are a major source of dietary-fibre in the Western diet. Cereal type (e.g. wheat, barley, oats etc.) has a major role in determining type and content of dietary fibre. Increased consumer consciousness has led to a demand for fibre-enriched products. Since dietary fibre is unevenly distributed within the cereal grain, the amount and type of fibre present in any cereal product will be dependent on the extent and method of processing. Bread is one such product, supplementing dough with brans or other sources of fibre requires changes to breadmaking practices.

1.3 BIOLOGICAL SIGNIFICANCE

The significance of dietary fibre lies in its physiological activity and as a consequence the roles it is postulated to play in the incidence of a number of disease states. Early enthusiasm for dietary fibre playing a role in the incidence

of a number of diseases was based on correlations between incidence and consumption data. Accurate estimations of fibre consumption are difficult and much of this type of work must be viewed with some degree of caution. The physiological effects of dietary fibre are determined by its physical-chemical properties which in turn are dependent on chemical composition. The major physical-chemical properties involved are: water binding capacity; viscosity; cation exchange; adsorption; microbial degradation and particle size. Dietary fibre exerts a variety of effects on the physiology of the alimentary canal. The degree to which these effects occur is dependent on the nature and source of fibre. Many dietary fibres increase transit-times for food from the mouth to the caecum, however passage through the large intestine is frequently accelerated, leading to an overall reduction in transit-time. Dietary fibre can also modify the rate and amount of nutrient uptake and the biochemical profile of the microflora inhabiting the large intestine. A number of disease states, including many involving bowel disfunction appear to respond favourably to increased consumption including, constipation, irritable bowel syndrome, colonic diverticulosis and possibly colorectal cancer. Other diseases notably those associated with elevated amounts of cholesterol (gall stones and coronary heart disease), diabetes mellitus, and obesity also appear to respond to high-fibre diets.

1.4 IMPLICATIONS FOR INDUSTRY AND THE CONSUMER

In the light of many of the physiological effects of dietary fibre being beneficial to the consumer, the advocacy by a number of learned bodies of increased fibre consumption and increasing public health consciousness, dietary fibre has considerable sales potential. Although sales of high-fibre cereal products such as wholemeal bread have increased in the UK, sales appear to have stabilised and fibre consumption does not appear to have increased to the same extent as in the USA. In promoting the sales of fibre-rich products manufacturers should be aware of forthcoming legislation which will specify how such claims can be made and what evidence they need to supply to justify such claims.

1.5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Dietary fibre was concluded to comprise one or a combination of, resistant starch, nonstarch polysaccharides and lignin. Estimating its consumption is made difficult by a variety of confusing factors. The early view that low fibre diets were characteristic of the First World while high fibre diets were associated with Third World countries appears to be unfounded. Dietary fibre modifies both gut function and the incidence of various disease states, the extent to which this occurs being dependent on the physico-chemical properties of the fibre. A number of recommendations regarding future research are made. These include: development of a unified assay system so that there is a common definition of what fibre is; the generation of better statistics concerning estimation of consumption of fibre by the general public; development of more cost-effective assays for predicting physiological effect; evaluating the effect of cooking and other methods of food-processing on the structure and function of dietary fibre and finally investigating the effects of dietary fibre on genuine predictors of human disease states.

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2. GLOSSARY OF TERMS AND ABBREVIATIONS

2.1 TERMS

Alimentary canal	A series of organs through which food is ingested (mouth) digested and nutrients absorbed into the organism's blood supply, the residue is expelled through the anus.
Anaerobe	An organism (usually bacterial) which can live in an environment devoid or low in oxygen.
Atherosclerosis	A disease, primarily of the large arteries, characterized by the formation of fatty plaques on the inner arterial walls, leading to obstruction of the blood supply.
Bile acid	A complex organic acid secreted in the bile, it has an emulsifying function in the process of digestion. Bile acids can undergo chemical modification by the colonic microflora.
Bran	The intervening layer between the outer (pericarp) and endosperm of a cereal kernel.
Caecum	The first part of the large intestine.
Carcinogen	Something which induces cancer.
Chyme	Partially digested food, produced in the stomach and discharged into the duodenum.
Commensal bacteria	Bacteria normally resident in the large intestine.
Dalton	Unit of atomic weight.
Endosperm	The bulk of the cereal kernel and prime starch store.

Epithelium	The outer cell layer of a tissue with contact with the exterior.
Germ	The embryo component of the cereal kernel.
Glucan molecule	A glucose polymer, e.g. starch or cellulose. The chemical structure of each polymer depends on how the individual glucose units are linked.
Lignin	A polymer found in plant cell-walls composed of phenyl-propane residues.
Lumen	The space within any tubular tissue.
Macronutrient	A dietary component capable of being utilized by the organism and consumed in large quantities (e.g. carbohydrate, protein and fats).
Microflora	A bacterial community (usually of many different species).
Micronutrient	A nutrient consumed in small quantities (e.g. vitamins).
Monosaccharide	A simple sugar monomer with the general formula $(CH_2O)_n$ where $n \geq 3$ (usually $n = 6$).
Morbidity	The incidence of a particular disease.
Mortality	The incidence of death due to a particular factor.
Omnivore	Someone who eats both animal and vegetable foods.
Pentosan	A sugar containing a 5-carbon ring.
Pericarp	The outer layer of the cereal kernel.

Peristalsis — Waves of muscular constriction which propel food through the alimentary canal.

Phospholipid — A lipid containing a phosphate group; a component of biological membranes.

Resistant starch — Starch refractory to the hydrolytic activity of appropriate enzymes secreted by the mouth and small intestine. Consequently some, or all resistant starch passes undigested into the colon.

Retrograded starch — Recrystallised starch, produced after cooking and cooling. Retrogradation takes place over a long period (days) and the extent to which it occurs is a function of the amylopectin content.

Thrombosis — Formation of a clot within a blood vessel.

Transit time — The period taken for food to travel through part or all of the alimentary canal.

Vegan — One who does not eat animal-derived food of any kind.

Vegetarian — One who does not eat animal-flesh (some vegetarians eat fish) but will eat other animal-derived products e.g. butter, milk, eggs.

Xenobiotic — A non-food chemical, foreign to the organism with a physiological effect.

2.2 ABBREVIATIONS

AOAC	Association of Analytical Chemists
CHD	Coronary heart disease
DHSS	Department of Health and Social Security

FAO	Food and Agriculture Organization
HDL	High density lipoprotein
IBS	Irritable bowel syndrome
IDDM	Insulin dependent diabetes (Type I diabetes)
LDL	Low density lipoprotein
NACNE	National Advisory Committee on Nutrition Education
NIDDM	Noninsulin dependent diabetes (Type II diabetes)
NSP	Nonstarch polysaccharide
pH	A logarithmic scale for measuring hydrogen ion concentration
SCFA	Short chain fatty acid
VLDL	Very low density lipoprotein
WBC	Water binding capacity

3. INTRODUCTION

Increased public awareness of links between diet and general health have created both problems and new opportunities for food manufacturers. The cereal-based food industry is particularly well placed to benefit from this new awareness, in that it is a major supplier of a dietary factor whose increased consumption has been advocated by the medical profession and which is regarded by some members of the public as a panacea - dietary fibre.

Although the term dietary fibre is an invention of the second half of the 20th century, its beneficial effects have been advocated for millennia. In the 4th century BC the Greek physician Hippokrates commented 'To the human body it makes a great difference whether the bread be made of fine flour or coarse, whether of wheat with the bran or wheat without the bran'. The introduction of new milling techniques in the 19th century led to much debate over the consequences of removing the fibre-containing portions (e.g. bran) on human health. The laxative properties of wheat bran were recognised early on and, as early as the 1920's, consumption of breakfast cereals containing bran was advertised as being beneficial to health (Vanderveen, 1986). Advocacy of dietary fibre's beneficial effects has only come to prominence in the last twenty to thirty years. Cleave (1966) proposed the 'Saccharine Disease' to be a condition comprising a number of diseases associated with the Western way of life and attributable to consumption of refined carbohydrates. This theme was taken up by Burkitt and Trowell (1975) who proposed that the low incidence in Africans of most of the chronic non-infective diseases found in the West was due to diet. They went on to propose that these diseases were caused by diets deficient in fibre rather than over-consumption of refined carbohydrates. These ideas have stimulated much research, in terms of dietary fibre's chemistry, physiological effects and its role in the aetiology of a number of diseases. The consequence of this research has been to generate a Pandora's box of information which has led some to regard dietary fibre more as a concept rather than an entity.

The objectives of this review are to: define the term dietary fibre; describe the role of cereals as a source from which it can be obtained; discuss the physiological effects of dietary fibre and their consequences for human health; identify areas for further research.

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4. NATURE AND SOURCES

4.1 INTRODUCTION

4.1.1 What is dietary fibre?

The term 'dietary fibre' is perhaps unique in nutrition, since it is a collective noun for a group of dietary constituents originally defined using physiological rather than chemical parameters. It was first used by Hipsley (1953) and resurrected by Trowell (1972). The latter defined dietary fibre as being the remnants of plant cell walls not digested by enzymes produced by the human alimentary canal. This term embraces a wide group of materials including polysaccharides, lignins, indigestible proteins and lipids, together with inorganic constituents of the cell wall. The definition was later modified to exclude indigestible proteins and lipids but to include nonstarch storage polysaccharides (e.g. guar gum, seaweed, polysaccharides and chemically modified celluloses). Cummings (1981) used a chemical approach and defined dietary fibre as 'nonstarch polysaccharides and lignin'. Such a definition still describes a heterogenous group and makes no allowance for materials produced during processing or cooking which may have similar physiological properties (e.g. resistant starch). The lack of an adequate definition has led some into the realms of metaphysics. For example, Heaton (1990) proposed that dietary fibre was not a 'collection of substances' but rather a 'spectrum of concepts'. In its general conclusions and recommendations, the British Nutrition Foundation's task force report on complex carbohydrates (1990) observed that use of the term dietary fibre frequently assumed a single chemical entity and was therefore imprecise. They suggested that, 'the word "fibre" should become obsolete, at least in the scientific literature' and that in future reference should be made to the source and composition of the material. Perhaps the best solution is to adopt the terminology of Spiller (1986) and refer to Plantix (PLANT matrIX) which may be defined as plant derived polysaccharides and lignin, resistant to the action of human digestive enzymes. However the words 'fibre' and 'dietary fibre' are well established in the public's sensibilities.

4.1.2 Chapter objectives

This chapter addresses the general chemistry of polysacharides and lignin, describes current methods for the analysis of dietary fibre and finally reviews the principal sources of cereal-derived dietary fibre and some of its interactions with cereal-processing and baking.

4.2 CHEMISTRY OF POLYSACCHARIDES AND LIGNIN

4.2.1 Polysaccharides

In general terms, polysaccharides are polymers built up of linked sugar molecule subunits (monomers). One definition of a polysaccharide (British Nutrition Foundation, 1990) is a molecule containing 20 or more monomers (anything less being termed an oligosaccharide). Many of the chemical and physiological properties of polysaccharides relate to the molecule's three dimensional (tertiary) structure, which in turn can be changed by reason of processing (e.g. milling) and/or cooking. This aspect can be important in determining whether a particular polysaccharide behaves as a 'fibre' (at least physiologically). Polysaccharides can be arbitrarily divided into two groups on the basis of their botanical function: storage (i.e. as a source of energy) or structural.

Storage Polysaccharides. Two storage polysaccharides are associated with cereals - starches and fructans. They differ chemically in that while starches comprise a single subunit (glucose), fructans have two subunits, glucose and fructose. In cereals the amounts of fructan compared with starch are low and the remainder of this section will be restricted to the starches. On a structural basis the starches can be divided into two broad groups: amylose, a linear molecule with an α 1-4 linkage (see Figure 4.1) and amylopectin, a branched molecule with both α 1-4 and α 1-6 linkages. Amyloses have molecular weights of approximately 60,000 daltons, a helical conformation and comprise 15 to 20% of isolated starch. Amylopectins form the bulk of the starches isolated and are heavier (in excess of 10^6 daltons) and have more complex tertiary structures than amyloses.

In their native state, starches exist as crystal-like granules. Analyses of starch granules (Katz, 1934; Wu and Sarko, 1978a,b; Hizukuri, 1985; Gidley, 1987) have led to the identification of three different structural types: type A, usually found in cereals; type B (raw potatoes and bananas); type C (legumes). Granule types B and C tend to be more resistant to enzymic digestion than type A. Native starch granules have a phospholipid coat which acts as a barrier to digestive enzymes.

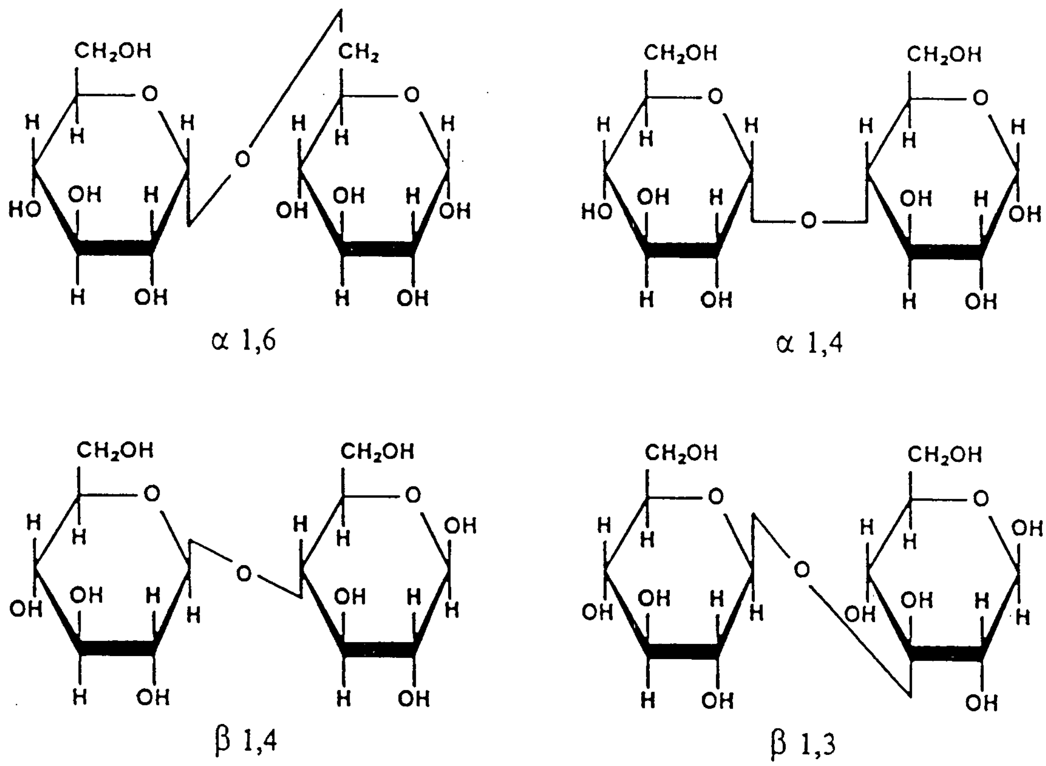

Figure 4.1 Structural linkages between glucose molecules in starches, cellulose and beta glucans

During cooking crystallinity is lost by the starch molecules assuming more randomly organised structures, leading to swelling and general thickening within the surrounding matrices (gelatinization). Consequently the starch is more susceptible to enzymic degradation and digestion. Since gelatinization depends both on the amount of water used and duration of heat treatment, cooking practices have an important role in starch digestibility. Cooling (or drying) leads, in part, to recrystallization (which can take some considerable time - days), the new structure-types being dependent on the original cooking and subsequent storage conditions. This process is termed retrogradation and is dependent on the amount of amylopectin present. Cooking conditions involving high temperatures and reduced amounts of water result in a type A crystalline structure, lower temperatures and higher amounts of water, in a type B crystalline structure (Wu and Sarko, 1978ab). The way food is prepared can therefore lead to the formation of starches less soluble and more resistant to enzymic hydrolysis <u>in vitro</u>

and digestion in vivo.

Englyst and Cummings (1987) proposed that cooked or processed starch could be nutritionally classified on the basis of their susceptibility to enzymic digestion. They proposed three classes: RDS (rapidly digestible starch), found in starchy foods cooked using moist heat (e.g. bread); SDS (slowly digestible starch), relatively resistant to digestion when compared to RDS but nevertheless will eventually be digested (associated with type A or C crystalline forms) and RS (resistant starch) which, to one degree or another, is refractory to enzymic digestion. Both RDS and SDS undergo complete digestion in the small intestine, however RS does not. Resistant starch itself can be divided into three types: RS_1, which owes its resistance to digestion due to the starch being physically inaccessible to digestive enzymes (e.g. partly milled grains); RS_2, resistant as a consequence of crystalline structure; RS_3, the most resistant to enzymic breakdown, which is predominantly recrystallised amylose produced from the cooling of gelatinized starch. Both RS_1, and RS_2, undergo partial digestion in the small intestine, RS_3 does not. This raises the question: should RS_3 be classified as dietary fibre? This question will be addressed later in the review.

Structural polysaccharides. Compared with an animal cell, the plant cell is physically more rigid. This is due to the presence of a cell wall comprising to a large extent polysaccharides and lignin. The cell wall's chemical composition reflects its function. Although not the major cell-wall polysaccharide, cellulose is always present. It is a glucan molecule with a ß 1-4 linkage (Figure 4.1), high molecular weight (0.5 - 1.0 x 10^6 daltons) and high degree of polymerization (between 300-1500; Theander, 1977).

The majority of cell wall polysaccharides are noncellulosic and are often referred to as NCP (Non Cellulosic Polysaccharides). This term describes a diverse group of molecules with differing physical and chemical structures. NCP's can be further subdivided into: Pectic substances. These are usually found in the primary cell walls and intracellular layers of land plants. Particularly high amounts are found in certain fruits (e.g. apples). Their essential molecular structure consists of a backbone of linked galacturonic acid molecules interspersed with rhamnose to which are attached side chains consisting of galactose, arabinose, xylose, rhamnose or glucose (Dreher, 1987). Molecular diversity can be further enhanced with esterification of the galacturonic acid residues by methyl or acetyl groups.

Beta-glucans. These are commonly found in the endosperm and aleurone cell walls of cereals, the highest concentrations being found in oats and barley (3.4 and 4.4% dry weight respectively compared with 0.7% for wheat; Henry, 1985). They are essentially glucose polymers with ß 1-4 linkages interspersed with ß 1-3 linkages. Hemicelluloses. These are widely distributed and are composed of mixed polymers of different sugar units with side chains consisting of galactose, arabinose and uronic acids (Dreher, 1987). Both cellulose and NCP are nonstarch polysaccharides, resistant to digestion by human alimentary canal enzymes. Therefore they can be regarded as dietary fibre as defined by Cummings (1981).

4.2.2 Lignins

Lignins are usually found in mature plant cells, providing them with mechanical strength and rigidity. Like polysacharides they are polymers. However, the subunits are phenylpropane residues rather than sugars. Lignins are formed by the condensation of phenolic alcohols (coniferyl, sinalpyl and p-coumaryl) to form long chains with molecular weights between 1,000 and 4,000 daltons. These in turn cross link to form a high molecular weight matrix-like molecule (Selvendran, 1984). The lignin content of plant-fibre can vary enormously from approximately 50% of the cell-wall for wood fibre compared with 6% in cabbage. The chemical structure of lignin is such as to render it totally indigestible by humans.

4.3 ANALYSIS

Despite difficulties in defining what dietary fibre actually is (4.1.1), its nutritional and commercial potentials have necessitated the development of suitable assays. Two assays are currently in extensive use, however they use different philosophies and can give different values for the same material.

The AOAC version as described by Prosky *et al.* (1984, 1985) and summarized in Appendix 4.1 is the approved method in a number of countries including Switzerland, USA and the Nordic countries and there are moves to adopt it as the standard EC method. On a world-wide basis it is probably the most used and lends itself to the requirements of food labelling and quality control. It and similar methods have been criticized on the basis that such assays measure a material which is ill-defined and that chemically it cannot predict physiological effects (see Schweizer, 1989). As Schweizer has pointed out, these criticisms seem unreasonable since no other methods for determining the composition of foods (e.g. total protein) predict physiological effect and that gravimetric residues can be further analyzed for their carbohydrate monomers and lignin if required. The AOAC method also measures resistant starch as dietary fibre. Although there is still debate as to whether resistant starch should be considered as fibre (Englyst *et al.* 1987; Asp *et al.* 1988), Schweizer *et al.* (1989) have shown that any starch present in the residue remains undigested in its passage through the small intestine.

The second method of analysis used is based on chemical methods and provides for a more chemically rigorous definition of dietary fibre. The Englyst method (Englyst *et al.*, 1982) currently favoured by the UK Ministry of Agriculture, Fisheries and Food is summarized in Appendix 4.2. It measures nonstarch polysaccharides (NSP) as their component monosaccharides and uronic acids after hydrolysis, it does not measure lignin or resistant starch (Englyst and Cummings, 1987), but can be easily adapted to measure resistant starch.

One of the problems now facing the food industry is which definition (and by implication which assay method) should be used. Although both methods give similar results for fruits and vegetables, the same cannot be said for cereal products. The AOAC procedure consistently gives higher values, which in some cases can be between 2 and 7 times (white flours milled from wheat and rice flours) higher than that using the Englyst method (Prosky and Harland, 1985). The choice of assay system must, in the end, depend on the reasons for assay. Is it to measure that fraction of the diet which has a particular physiological property (resistance to enzymic digestion) or to a more rigorous chemical definition (NSP)?

4.4 SOURCES

Dietary fibre is associated with many plant derived food-stuffs. For the purposes of this review, this section will be restricted to cereals. Since the cereal grain is not a uniform structure, cereal-derived foods come from a variety of genetically distinct organisms and are produced by diverse processes, the source of dietary fibre is clearly important.

4.4.1 Distribution of fibre within the grain

Elchazly and Thomas (1976) have provided data on the nature and amounts of fibre associated with various parts of the wheat kernel. Their data are summarised in table 4.1 and reveal that not only the amounts but also the chemical compositions of fibre recovered from kernel fractions are different. For example bran fibre contained the greatest amount of lignin (24%). Also more hemicellulose than cellulose was found in the pericarp and bran layers, but the reverse was true in the endosperm and germ. It can be concluded that although all parts of the kernel contain some fibre, its distribution is uneven. Thus while the pericarp was 73% fibre, the endosperm was only 2.3%.

Table 4.1 Distribution of total dietary fibre, crude hemicellulose, crude cellulose and crude ligin in the four major parts of the kernel (All data expressed as g/100g dry weight)

Tissue	Proportion of whole tissue (%)	Total dietary fibre	crude hemicellulose	crude cellulose	crude lignin
Pericarp (outer husk)	3.28	73.04	48.10	23.44	1.50
Bran layers (without pericarp)	18.33	23.00	9.83	7.67	5.44
Endosperm	76.00	2.31	0.90	1.10	0.31
Germ	2.39	9.61	3.62	4.84	1.15

A whole wheat grain was determined to have 8.60g total dietary fibre/100g dry weight of which 4.20g/100g dry weight was hemicellulose, 3.10g/100g dry weight, cellulose and 1.30g/100g dry weight lignin.

After Elchazly and Thomas (1976).

4.4.2 The role of milling

From the above, it becomes apparent that milling efficiency will determine the amount of fibre associated with any flour produced. Nyman *et al.* (1984) analysed the fibre content of flour from a variety of cereal sources at various extraction rates (Table 4.2). With wheat flour they observed no change in fibre content at extraction rates of between 66 and 80%, after which it increased. This result contrasted with the other flours where fibre content rose with extraction rate throughout the range studied (66-100%). However, it should be noted that the kinetics by which the increase occurred were different for the different cereals used.

4.4.3 Cereal source

Consideration of Table 4.2 reveals that not only the amount but also the chemical composition of fibre associated with different cereals varies. Marked intraspecies variation in fibre content have also been observed. For example, Baker (1978) determined the fibre content of six different wheat varieties and found their fibre content to range from 10.3 to 12.7%. Of greater physiological importance is

Table 4.2 Fibre content of flours prepared from wheat, rye, barley, sorghum, rice and corn at two different extraction rates (all data expressed as g/100g dry weight)

	Extraction Rate %											
	Wheat		Rye		Barley		Sorghum		Rice		Corn	
	66	100	66	100	66	100	66	100	66	100	Fine	whole
Polysaccharides	2.4	9.5	6.8	12.5	7.9	15.1	2.3	6.7	1.1	13.0	4.1	8.0
Lignin	ND	2.0	0.3	2.1	ND	3.5	0.4	2.5	ND	3.9	0.8	1.4
Total	2.4	11.5	7.1	14.6	7.9	18.6	2.7	9.2	1.1	16.9	4.9	9.4

ND = not detected

After Nyman *et al.* (1984)

variation in the chemical composition of dietary fibre. Henry (1985) directed his attention to the polysaccharide fraction of fibre and analysed NSP from a variety of cereals (data summarized in Table 4.3). He observed that not only did the amounts of pentose-based and ß-glucan polysaccharides differ in different cereals but also that their ratio to one another also varied. The physiological consequences of these differences will be discussed in the following chapter.

Table 4.3 Total pentosan and ß-glucan contents of cereal grains (data expressed as % dry weight)

Cereal	Total Pentosan	Total ß-glucan	Ratio Pentosan/ß-glucan
Barley	5.69	4.36	1.31
Oat	7.65	3.37	2.27
Rice	1.18	0.10	ND
Rye	8.49	1.89	4.61
Wheat	6.63	0.65	10.2

After Henry (1985)

4.4.4 Fibre and bread production

Increasing public demand for high-fibre products has inspired investigators to research the interactions between the cooking process and fibre content of cereal-based foods. These studies have addressed questions regarding the consequences of cooking on fibre structure, content and the effects of supplementing recipes with additional fibre. Since cereals are used in the production of many foods, the consequences of food procesing on fibre will only be discussed in relation to bread.

The effect of cooking on starch structure and the potential for producing resistant starch (which has physiological properties similar to the NSP component of fibre) has already been discussed (4.2.1). The effects of baking on the fibre-content of white bread have been described by Aman et al. (1990). They observed that the pentosan component of NSP present, decreased during baking, probably due to thermal degradation. This conclusion was based on observations that the effect was greatest in the outer crust fraction and least in the inner crumb and that degradation increased as a function of baking-time. The solubility and physico-chemical properties of the NSP fraction were also altered as a consequence of baking. Since the physiological effects of dietary fibre depend on these parameters (see following chapter), changes in structure affected by cooking methods (e.g. baking) may have important nutritional implications.

As Dreher (1987) has pointed out, bread is one of the oldest and most widely consumed sources of dietary fibre and although consumption of whole-wheat and speciality breads has increased, there is a demand for a fibre-enriched conventional loaf. Various groups have evaluated the consequences of substituting dietary-fibre for some of the white wheat flour used in bread manufacture. Pomeranz *et al.* (1977) evaluated the effects of substituting up to 15% of wheat flour with one of a number of fibre sources (wheat or oat brans or cellulose) on bread making. With the exception of loaf volume (which fibre substitution always reduced), the effects were not uniform. Addition of wheat-bran or cellulose increased dough water absorption, oat bran decreased it. Similarly dough mixing times were unaffected by the addition of bran, but increased by oat bran or cellulose. In contrast D'Appolonia and Youngs (1978) reported increased Farinograph water absorption and reduced mixing times when oat or wheat bran at amounts of 10 or 20% were used. Like Pomeranz *et al.* (1977) they too observed reduction in loaf volumes.

Collins and Hook at the Flour Milling and Baking Research Association have investigated the conditions necessary for the production of customer-acceptable wholemeal bread (expanded loaf). In their papers (Hook and Collins, 1987; Collins and Hook, 1988) they made three major conclusions.

Milling. Control of the milling process will lead to improved bread production. Particle size, profile and composition were identified as being important. For example flour produced from processes yielding coarse particles with low water absorption yields low-volume bread. Best quality loaves are produced using meal of fine particle size with good bran/endosperm separation. However, too-fine bran will change bread characteristics.

Bread Making Method. The Low-Speed Mixing method is more sensitive than the Chorleywood Bread Process to the different wholemeal characteristics (particle size etc.).

Fortification. The grist and gluten fortification requirements depend on the bread making process used. If the Chorleywood Bread Process is used, an all English grist plus gluten can be satisfactory. However, with the Low-Speed Mixing method native protein will be more successful.

Dubois (1978) made a number of recommendations concerning fibre supplementation of bread. In summary, he observed that fibre supplementation should not exceed 7%. He reported that adding fibre in greater amounts requires substantial changes in the bread making process. These were due primarily to gluten-dilution (resulting in weakened cell structure and poor gas retention) and fibre-based flavours which might be antagonistic to those acceptable to bread flavour. These recommendations have been adapted for the Chorleywood Bread Process and are detailed in Appendix 4.3.

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Appendix 4.1

Analytical scheme for the AOAC method for determining dietary fibre

Sample (1g)

Termamyl (pH 6.0; 100^{o}C; 15-30 min)
B. subtilis protease (pH 7.5; 60^{o}C; 30 min)
Amyloglucosidase (pH 4.5; 60^{o}C; 30 min)

Precipitation with 4 vols ethanol
Filtration

Residue
Correction for protein and ash

TOTAL DIETARY FIBRE

After Schweizer, 1989

Appendix 4.2

Analytical scheme for the Englyst method for determining dietary fibre

Sample

Disperse starch in dimethyl sulphoxide

Hydrolyse starch with α-amylase and pullulanase

Precipitate NSP with ethanol

Acid hydrolysis

NEUTRAL SUGARS
&
URONIC ACIDS

neutral sugars + uronic acids = total NSP

Appendix 4.3

Recommendations for good production of fibre-enriched breads

1. Use strong flour.

2. Add sufficient water to hydrate both the fibre and gluten.

3. Gluten dilution to be compensated for by addition of extra vital gluten.

4. Yeast requirements unaltered.

5. Salt content to be increased slightly.

6. Increase fat content to 2%.

7. A wide selection of dietary fibres can be used, but wheat bran is the most common.

5. BIOLOGICAL SIGNIFICANCE

5.1 INTRODUCTION

The significance of dietary fibre lies in the role it plays, or is postulated to play in a variety of human disease states. To one degree or another the mechanisms underlying these roles are consequences of the physicochemical properties of dietary fibre and its activity within the alimentary canal. This chapter gives estimates of fibre consumption, discusses the physical-chemistry of dietary fibre and finally relates this information to the interactions between fibre and human gut function or disease.

5.2 CONSUMPTION

Much of the early enthusiasm for the beneficial effects of dietary-fibre was based on epidemiological studies correlating the mortality/morbidity of a disease within a particular population with its fibre consumption. However, estimating the consumption of any dietary component, on a population basis, is difficult (Bingham, 1985). Studies such as those of Bingham and Cummings (1980) and Bright-See and McKeown-Essen (1984) have shown that not only quantity but also the source of dietary fibre changes internationally. *Per capita* consumption in Eastern Africa is usually in excess of 100g fibre per day, this compares with values of less than 30g per day (median value between 22 and 24g per day) for the Western World (Bright-See and McKeown-Essen; 1984). These data were calculated from a FAO Food disappearance report (FAO; 1977). *Per capita* fibre intake for the UK was estimated to be 22.4g per day. Of greater interest is the proportion of dietary-fibre consumed which is attributable to cereal-based products. This varies on a national basis. Using the data of Bright-See and McKeown-Essen, a comparison of countries with a fibre consumption within the median range (22-24g per day), revealed that cereal-derived fibre accounted for 31.8% of total fibre intake in the UK, through 43.6% in Sweden to 60.9% in Denmark. This compares with actual daily *per capita* dietary fibre intakes of 22.4g, 22.4g and 23.9g dietary fibre per day respectively.

Caution must be applied in the interpretation of such data since there can be considerable interpersonal variation in consumption. This is most marked, when considering subsets of a national population with widely differing dietary practices. Davies *et al.* (1985), working in the UK, found that daily *per capita* fibre consumption was 25g per day in omnivores and rose to 36g per day in vegetarians and 47g per day in vegans. Variation within a random sampling can also be considerable. In one such group, Bingham *et al.* (1980) determined average fibre intake to be 19.9 $\pm$ 5.3g per day (mean $\pm$ standard deviation), the range was between 8 and 32g per day. Other types of variation (temporal or analytical) can also act as confounding factors in estimating fibre.

Two factors contribute to temporal variation, the first is seasonal. Bingham (1985) analysed the results of the British National Food Survey for each of the four quarters of the year 1974-75. Consumption was lowest in the second quarter (April-June) and highest in the fourth (October-December). These changes may be due to the seasonal availability of fruit and vegetables. Daily variation in consumption can be great. Dreher (1987) quotes one man's daily dietary fibre intake over a 4 day period as being 37, 29, 10 and 14g. per day. The second major problem is the method of analysis used. As stated earlier (4.3) different analytical techniques measure to different end-points. Care must therefore be used in defining exactly what is meant by the term 'dietary-fibre' (see 4.1.1).

5.3 PHYSICAL-CHEMISTRY OF DIETARY FIBRE

The extent to which dietary fibre interacts with human physiology depends on its physical-chemical properties. These in turn are dictated by the composition of the fibre. Pomeranz (1985) has identified four contributing factors to fibre composition:

1. Molecular composition: the chemical identities and amounts of constituent monomers.
2. Chemical modification: the degree, positioning and type of functional groups present on the component monomers.
3. Structure: how the component monomers are chemically linked, the degrees of branching and polymerization.
4. Conformation: the overall shapes of the molecules and their spatial relationships.

Dietary fibre has six physical-chemical properties which singly or in combination can influence physiological effect. The extent to which any fibre possesses these properties depends on its source, composition and degree to which it has been processed.

5.3.1 Water binding capacity

Water binding capacity (WBC), water holding capacity and water-hydration capacity are synonyms used in the literature to describe the capacity of fibre to retain water within its matrix (Dreher, 1987). The WBC depends on particle size and chemical composition. Generally speaking, WBC values are highest in fibres with large particle sizes and high hemicellulose and pectin contents. Water associates with fibre in one or a combination of three forms: tightly bound - only removed by severe processes such as freeze drying; firmly held - can be removed under pressure but not by centrifugation; loosely associated - water which can be removed by gentle methods e.g. filtration. No standard method for measuring WBC exists, it can be determined using centrifugation or dialysis techniques (McConnell *et al.*, 1974) or glass columns (Anderson and Eastwood, 1987). Despite methodological differences it is possible to make comparisons between foods, WBC range from 3.0g water per g fibre to 4.24g per g fibre for fruit or vegetables (McConnell *et al.*, 1974).

5.3.2 Viscosity

Some soluble fibres have the ability to form viscous solutions. This ability is dependent on a number of factors including concentration, molecular structure, shear conditions, pH, WBC, and the nature of the solvent. Generally, fibres with high WBC values form the most viscous solutions.

5.3.3 Cation exchange

Minerals are made available as charged particles (ions) which are either positively (anion) or negatively (cation) charged. Fibres rich in acidic polysaccharides have the ability to bind cations and inhibit uptake from the alimentary canal (see also section 5.4.3).

5.3.4 Adsorption

Noncharged compounds can also associate with fibre and therefore not be taken up. This process is termed adsorption and is associated with the lignin, pectin and hemicellulose components of fibre.

5.3.5 Microbial degradation

By definition (4.1.1) dietary fibre is resistant to digestion by enzymes synthesized by the alimentary canal proper. However, the polysaccharide component of fibre can, to a degree, be utilized by bacteria resident in the colon as an energy source. As a consequence, changes in microbial metabolism occur leading to production of metabolites with differing physiological effects.

5.3.6 Particle size

Particle size plays important roles not only with regard to physiological effect *per se* but also in modifying some of the physical-chemical properties described above. For example it has been demonstrated that reducing the particle size of wheat bran reduced its WBC, however the reverse was observed with oat bran (Cadden, 1987). Particle size will also determine the surface area of the fibre, a factor which contributes to efficacy of fibre's binding properties.

5.4 THE PHYSIOLOGICAL EFFECTS OF DIETARY FIBRE

5.4.1 Structure and function of the alimentary canal

Since by all definitions, dietary fibre is resistant to breakdown by enzymes produced by the tissue comprising the alimentary canal, it is this organ where fibre exerts its direct effect. No discussion of the effects of dietary fibre on human physiology and disease state can be made in the absence of some description of the structure and function of the alimentary canal.

Essentially it is a long and sometimes convoluted tube with two points of contact with the outside world - the mouth and the anus (for diagram see Appendix 5.1). Food is ingested via the mouth, processed and absorbed within the canal and the residue expelled via the anus. However, the system is more complex with structurally distinct organs of different function. Breakdown of food to an absorbable form begins on ingestion both mechanically (mastication) and enzymatically (starch digestion by salivary amylase). Food passes down to the stomach where mechanical disruption continues in the presence of secreted hydrochloric acid and a proteolytic enzyme - pepsin. The product of this process - chyme is expelled into the duodenum. Here it is brought to near neutral pH by the secretion of bicarbonate and exposed to the action of a cocktail of digestive enzymes produced by the pancreas. Fat digestion is assisted by the presence of an emulsifying agent - bile, produced by liver and stored in the gall bladder. Other digestive enzymes are produced by the small intestine proper. The small intestine is also the site where nutrients are absorbed into the organism via the blood supply. Undigested food passes into the large intestine, which is primarily a site of water absorption (although some other molecules are absorbed). The large intestine is also residence to a substantial population of (usually) commensal bacteria, some of which produce enzymes which can digest residual food including the polysaccharide component and use it as a carbon source. After passing through the large intestine, the remainder (a mix of undigested food, sloughed-off intestinal cells, secretions and bacteria) is discharged through the anus. Movement of material through the alimentary canal is achieved by continuous waves of constriction - a process termed peristalsis.

5.4.2 Dietary fibre and food transit

Experiments performed by McCance *et al.* (1953) demonstrated that diets containing bread baked from whole-wheat flour took longer to eat than those containing white (70% extracted flour) bread (45 versus 34 minutes). As well as retarding ingestion, dietary fibre also promotes satiety. Possible mechanisms for this and its role in the management of obesity will be discussed subsequently (see 5.6.8). Dietary fibre also modifies the speed at which food passes through various sections of the alimentary canal. For example, Grimes and Goddard (1977) demonstrated that gastric emptying was slower when patients ate wholemeal bread as opposed to white bread. This effect appears to be dependent on the viscosity and WBC of the fibre, fibres such as guar gum and pectin being more effective than wheat bran (Holt *et al.* 1979). Fibres of high viscosity (e.g. ß-glucans from oats) tend to retard food-transit from mouth to caecum (Blackburn *et al.* 1984). This process may be due to fibre contributing to the increased resistance of luminal contents to propulsion and to a reflex slowing brought about by nutrients which failed to be absorbed in the jejunum acting at ileal receptor sites (Read *et al.* 1984).

In contrast to the above, dietary fibre speeds transit of material through the large intestine. The effect is so marked that the overall mouth to anus transit time is considerably shortened. This phenomenon has been observed in many human studies (e.g. Stasse-Wolthurs *et al.* 1978) and there are a number of factors, alone or in combination which contribute to it.

WBC. Stephen (1985) observed an inverse relationship between stool weight (bulk) and fibre WBC (increases in bulk promote reduced transit times; Spiller *et al*, 1977). Although a high WBC indicates a greater bulking ability, it is also suggestive of increased susceptibility to bacterial degradation. Therefore fibres with high WBC values may have less of an effect on faecal weight. Thus, source of fibre plays an important role, consumption of oat bran has been observed to lead to a 15% increase in stool weight compared with 100% for wheat bran (Schneeman, 1986).

Particle size. Experiments performed by Kirwan *et al.* (1974) and subsequently confirmed by Brodrick and Groves (1978) demonstrated that eating large (as opposed to small) particles of wheat bran was more effective in increasing stool weight and reducing transit time. These results may be due to coarser bran having a higher WBC (although still being resistant to fermentation), giving greater bulking potential and/or that the particulate nature of bran stimulates peristalsis (Tomlin and Read; 1988ab).

Bacterial fermentation. Although bacterial fermentation can result in the structural breakdown of fibre, it also leads to increased bacterial growth and numbers. This, in turn, can result in increased stool weight. Cummings *et al.* (1978) observed that cabbage fibre (which is readily fermented) increased human stool weights by 69%. This increase was attributable mainly to an increase in bacterial weight and to a far lesser degree residual hemicellulose. In contrast, wheat bran (comparatively resistant to fermentation) increased faecal bulk by 127%.

5.4.3 Dietary fibre and the digestion and absorbtion of nutrients

The processes by which food is broken down to its component molecules (digestion) and absorbed into the organism have mechanical, physical and chemical attributes which can be modified by dietary fibre. Since some definitions express dietary fibre as material originating from plant cell walls, failure to break down such walls by processing (e.g. milling) and/or cooking will render plant-cell contents more difficult to digest and absorb (Johnson, 1990). There is little evidence that dietary fibre modifies the effects of the digestive enzymes secreted into the small intestine, although Khokher and Kapoor (1990) have shown that some high fibre sources can reduce protein digestibility in animal models.

Dietary fibre appears to affect the absorption of macronutrients (sugars, amino acids, lipids, etc) by modifying the physical and mechanical properties of both the wall (epithelium) and lumen of the small intestine. Transport of nutrients through the lumen to the epithelium, where absorption occurs, involves two stages. Turbulence and convective currents produced by peristalsis bring nutrients from the lumen close to the epithelium (Macagno *et al.* 1982). They must then diffuse through a thin layer of static fluid ('unstirred layer') before being absorbed (Blackburn *et al.* 1984). Dietary fibre appears to reduce nutrient absorption at both stages. Evidence exists that fibre (in particular viscous fibre) provides resistance to the convectional effects of peristalsis (Phillips, 1986; Edwards *et al.* 1988) leading to reduced luminal mixing and additionally increases the apparent thickness of the unstirred layer (Johnson and Gee, 1981). The role of dietary fibre in the absorption of macronutrients has been investigated with regard to various disease states and will be dealt with in a following section (5.6). The remainder of this section will address the effect of dietary fibre on mineral absorption.

Since the war-time experiments of McCance and Widdowson (1942), who observed reduced iron absorption in persons consuming brown as opposed to white bread, the effect of dietary fibre on mineral balances has been the subject of controversy (Kelsay, 1986) and concern by some regulatory bodies (Canadian Advisory Committee on Dietary Fibre, 1985). The potential of fibre to promote malabsorption of minerals has been attributed to one or a combination of the following: its ability to act as a cation exchanger; induction of reduced transit time; dilution by increases in faecal bulk (Kay, 1982). The interactions and the absorption of two minerals, calcium and iron have been particularly well studied.

Calcium. Although *in vitro* experiments indicate that wheat bran has little affinity for calcium (Randlemen, 1982), human studies have shown that while short-term (29 days) consumption of 11g of additional dietary fibre (from wheat bran) had no effect, increasing consumption to 35g per day yielded a negative calcium balance (von Dokkum *et al.* 1982). Epidemiological studies have shown that very high fibre intakes have adverse effects on the calcium balances of certain groups (e.g. postmenopausal women, the elderly and infants (Person *et al.* 1976; Zoppi *et al.* 1982)

Iron. Fernandez and Phillips (1982) observed that, *in vitro*, iron could bind to fibre and in particular the lignin fraction. However, in humans, fibre does not appear to be associated with iron-deficiency diseases. For instance Reinhold *et al.* (1982) found no correlation between iron-intake anaemia and dietary fibre consumption in Mexicans.

Although dietary fibre has been adversely linked with the uptake of minerals in some population subsets, there appears to be substantial evidence (reviewed by Dreher, 1987) that persons on high fibre diets (e.g. vegetarians) adapt their mineral metabolism in response to their diet. Clearly, in the case of high-risk groups (e.g. postmenopausal woman at risk of osteoporosis and growing infants) counselling should be given with regard to the need for mineral supplements.

5.5 DIETARY FIBRE AND THE GUT MICROFLORA

The large intestine acts as residence for a varied population of bacteria, with diverse metabolic capacities frequently different to that of the host. Over 12 genera of bacteria have been isolated and their genetic diversity makes it advisable to discuss the effects of dietary variation in terms of overall biochemical activities rather than changes in a particular subpopulation. Nutrients for these bacteria enter the colon as undigested food, nonabsorbed nutrients, gut secretions and intestinal cells. The colon has a low oxygen tension and the bacteria found there are generally anaerobes (i.e. grow in the absence of oxygen). Although, by definition, refractory to digestion by enzymes produced by the alimentary tract, the polysaccharide component of dietary fibre can be utilized as a carbon source by some of the resident bacteria. Members of genus Bacteroides have been shown to degrade both cellulose and hemicellulose (Betian *et al.* 1977, Reddy *et al.* 1983).

Bacterial metabolism of dietary fibre leads to the production of compounds which can be utilized by other bacteria or the host itself. Perhaps the most significant are short chain fatty acids (SCFA). Bacterial production of SCFA in the gut has been recognized since the early part of this century (Fischer, 1913). The influence of diet on the process has also long been recognized, Grove *et al.* (1929) observed higher faecal SCFA excretion after consumption of high starch or cereal based diets. SCFA production has a number of beneficial consequences for the host:

Increased osmality. Water is removed from the colon by osmotic equilibration with the blood supply, since osmosis is a colligative property (i.e. dependent on the number of molecules present in solution), breakdown of one polysaccharide molecule into 20-2000 smaller molecules will increase osmality and promote water retention in the colon, which in turn will contribute to faecal bulking (Stephen and Cummings, 1980).

Colon maintenance. SCFA produced in the colon can be absorbed into the host and can contribute to its energy balance. Of particular interest is butyric acid which is the major source of energy for colonic mucosal cells in vitro (Roediger, 1982) and enhances colon cell maintenance in humans (Scheppach *et al.* 1990). Roediger (1982), has proposed that a low fibre intake may lead to 'butyrate starvation' and to consequent degeneration of colon leading to clinical conditions such as inflammatory bowel disease.

Colonization resistance. The more diverse the established bacterial community the more resistant it is to opportunist pathogen infection. SCFA and other endproducts of fermentation promote this diversity and therefore probably contribute to colonization resistance.

Bacteria present in the colon are capable of performing a large number of molecular transformations which have implications for the status of the host organism. Many of the enzyme activities involved are susceptible to modification by changes in diet (Rowland *et al.* 1983). Goldin *et al.* (1980) observed that humans consuming wheat-bran showed no difference in ß-glucuronidase, azoreductase or nitroreductase (enzymes associated with xenobiotic metabolism) activities but reduced steroid dehydroxylase activity. Wheat bran also reduces deoxycholic acid production (Low-Beer, 1979). As will be discussed subsequently (section 5.6.6) the presence of deoxycholic acid is a causative factor in the aetiology of gall stones and has been postulated by some to have a detrimental role in colon carcinogenesis (Hill, 1986). Other beneficial properties associated with wheat bran consumption are a decreased catabolism of phenolic amino acids to volatile phenols (Cummings *et al.* 1979) and increased ammonia utilisation which may be of importance in reducing the protein sensitivity of patients with liver or renal failure (Rowland *et al.* 1983).

5.6 DIETARY FIBRE AND DISEASE

Probably the most significant feature of dietary fibre is its advocacy by many as a potential cure or means of prevention of some diseases. Some of the mechanics by which fibre is supposed to exert its effects are not directly due to interactions between fibre and the digestive system but to their consequences on whole body physiology. This section will review evidence for the involvement of the physiological conditions that underly these disease states and whether such interactions are actually significant with regard to treatment or prevention.

5.6.1 Constipation and irritable bowel syndrome

Historically, abnormal bowel function was the first disease for which dietary fibre has been held as having a palliative effect (see reference to Hippokrates, section 3). For this review, abnormal bowel function will be used to cover the conditions of constipation and irritable bowel syndrome (IBS).

Constipation. This condition is experienced by most at some point in their lives. Due to differing perceptions it is difficult to define in straight-forward physiological terms (Moore-Gillon, 1984). Smith (1978) defined constipation as a sustained increased effort to defecate, others (British Nutrition Foundation, 1990) have defined it as a stool output of less than 35g/day or a mean transit time in excess of 72 hours. Constipation may be caused by any of a number of factors (reviewed by Painter, 1980) reflecting: personal psychology; bowel motility disorder (-simple constipation) other bowel diseases e.g. colon cancer (-secondary constipation). Simple constipation has been regarded by some as a fibre deficiency disease, easily cured by increased fibre consumption (Painter, 1980). This contention has now been challenged. Johnson *et al.* (1980) and Preston and Lennard-Jones (1986) have demonstrated that fibre consumption by constipation sufferers can be less, the same or greater than that of nonsufferers. Cummings (1984) proposed that constipation should be regarded as a motility disorder which in some cases responds to the mild laxative quality of fibre.

Although neither a complete nor always effective cure for some patients (Muller-Lissner, 1988), wheat bran has been well known for its laxative effects, most probably owing to its stimulation of bowel motility. It may act by increasing stool weight, number and bulk (Burkitt *et al.* 1972; Manning and Heaton, 1976; see also section 5.4.2).

Irritable bowel syndrome (IBS). This term is used to describe a disease state characterised by a change in defecation pattern with one or a combination of the following symptoms: constipation; diarrhoea; abdominal distension, discomfort or pain. It is a disease of exclusion in that it is diagnosed when routine clinical examination can provide no explanation for the symptoms. Wheat-bran has been advocated as a first-line method of treatment (Manning *et al*, 1977). However, the condition has a psychosomatic component and shows a marked response to placebos (Cann *et al.* 1984). Lucey *et al.* (1987) demonstrated that in placebo-controlled experiments wheat-bran and the placebo had similar overall effects. The only symptom of IBS for which there is definite evidence for alleviation by wheat bran is constipation (Cann *et al.* 1984).

5.6.2 Colonic diverticulosis

Colonic diverticulosis (diverticular disease) is a degenerative disease of the colon, prevalent in Western populations and characterised by outpouchings of the mucosal lining through the muscle wall of the colon (Berry, 1990). It is a disease associated with ageing and can be viewed as consequential to weakening of the muscular wall of the colon. Painter (1973) proposed diverticulosis to be a fibre-deficiency disease. Evidence from human studies is not substantive, epidemiological studies such as those of Gear *et al.* (1979) reveal that the incidence of the disease is lower in vegetarians who have higher fibre intakes. Evidence from animal studies is far stronger. Life-span studies in rats such as those of Fisher *et al.* (1985) have demonstrated an inverse relationship between the amount of fibre consumed and the incidence of diverticulosis.

Clinically, dietary fibre alleviates two of the disease symptoms - high colonic pressure and small stools. Findlay *et al.* (1974) observed a prophylactic effect with wheat bran. Although the source of wheat bran was immaterial (Smith *et al.* 1981), the potency of effect was dependent on particle size, coarse being more effective than fine (Broadribb and Groves, 1978) and cooking which can reduce the effect (Wyman *et al.* 1976).

5.6.3 Colorectal cancer

Colorectal cancer is a major cause of death in the Western world (approximate UK mortality = 33,000 per year), with the highest incidences in Western Europeans and North American Whites. Its most remarkable features are its unequal geographic distribution and the lack of an overall (but not individual) genetic element. These features have prompted many to identify statistical significance between morbidity and dietary habits. A strong positive correlation between dietary fat and incidence of the disease has been demonstrated (e.g. Correa, 1981). Similar studies initially revealed a slight but significant correlation between the size of the pentosan fraction of dietary fibre consumed and morbidity (Bingham *et al.* 1979). However, reanalysis of the methodology led the authors to retract this conclusion (Bingham *et al.* 1985). A recent review by Riboli (1987) of studies investigating links between dietary practice and morbidity revealed that no conclusions could safely be made (out of 19 studies 6 showed a negative correlation, 6 a positive one and 7 no correlation at all). Similar conclusions can be made from animal studies where colon cancer is induced by specific carcinogens (Kritchevsky, 1986).

5.6.6 Diseases linked with cholesterol metabolism

Cholesterol is a planar heterocyclic molecule synthesized in most tissues and is important both in the maintenance of the cell membrane and as a precursor for other biologically-active molecules. Like other nutrients absorbed in the small intestine, cholesterol is transported to the liver. There it has number of fates. It can undergo further metabolism. It can be excreted in the bile or it can enter into the general blood supply. Cholesterol is frequently transported through the blood supply complexed as either very low density lipoprotein (VLDL) particles or as high density lipoprotein (HDL). VLDL (but not HDL) can be modified in the blood leading to the release of fat and the generation of intermediate density lipoprotein (IDL) which can undergo further metabolism in the liver or other tissues to form low density lipoprotein (LDL). This aspect of cholesterol metabolism is important in the aetiology of two diseases prevalent in the West - gall stones and coronary heart disease, both of which are associated with elevated amounts of serum cholesterol and LDL.

The role of dietary fibre as a modifying factor with regard to human serum chemistry has been studied for some time. Studies by Kay and Truswell (1977) and Goriot et al (1986) failed to reveal a hypocholesterolaemic effect due to wheat bran (low in soluble fibre). In contrast studies such as those of Kirby et al (1981) revealed cereals rich in soluble fibre (e.g. oat bran) to reduce serum cholesterol concentrations. However, it should be noted that the hypocholesterolaemic effects were reduced in patients with lower initial plasma cholesterol levels. Oat bran appears to exert its effect by one or a combination of the following mechanisms.

Bile acid metabolism. Soluble fibres such as the ß-glucans present in oat bran may alter bile acid metabolism and reabsorption and oat bran has been observed to increase faecal-bile-acid excretion (Anderson *et al*. 1984). Since cholesterol is a precursor in bile acid synthesis this may result in a drain on cholesterol reserves.

SCFA production. As pointed out in section 5.5, fermentation of both NSP and resistant starch lead to the production of SCFA which are absorbed from the large intestine. Chen and Anderson (1986) have shown these to inhibit cholesterol synthesis in the liver and other organs.

Dietary modifications. Swain *et al.* (1990) observed that similar hypocholesterolaemic effects could be observed in subjects fed either a high oat bran or low fibre diets, providing both were low in foods rich in saturated fats. They concluded that switching to a high bran diet might exert its effect as a consequence of reduced fat intake brought about by changes in dietary habits. The role of dietary fibre in two cholesterol-linked diseases, gall stones and coronary heart disease will be discussed here.

Gallstones. Gallstone disease (cholelithiasis) is associated primarily with the Western world and afflicts approximately twice as many women as men (Heaton, 1981). They form in gall bladder bile when three conditions are met: the bile becomes supersaturated with (usually) cholesterol or another component of gall stones; nucleating factors are present and that gall bladder emptying is impaired so promoting crystallization (Heaton, 1986). Another factor associated with cholesterol supersaturation is the concentration of secondary bile acid deoxycholic acid (Heaton, 1986).

Evidence in support of dietary fibre preventing gallstones rests more on physiological experiments rather than epidemiological studies. A number of studies have demonstrated that increased fibre consumption leads to a reduction in risk factors associated with the disease. Thornton *et al.* (1983) observed that increased fibre consumption led to a reduction in biliary cholesterol, frequently to concentrations that were no longer supersaturating. The amount of cholesterol in the bile appears to be dependent on the quantity of deoxycholic acid produced since measures which lower bile deoxycholate also reduce cholesterol saturation (Marus and Heaton, 1988). Dietary fibre such as wheat-bran may exert their effects in specific and non specific manners (Heaton, 1988). These include binding of deoxycholic acid to fibre making it unavailable for absorbtion in the large intestine or fibre being fermented by bacteria in the large intestine leading to a shift to a more acidic pH and consequent precipitation of deoxycholic acid which is then voided in the faeces.

Thusfar epidermiological evidence has been unforthcoming. Studies by both Scragg et al (1984) and Pixley and Mann (1988) found no difference in estimated fibre consumption between patients with gallstones and nonsufferers. This failure may, in part, be a reflection on the problems associated with estimating fibre consumption in humans (see section 5.2).

Coronary heart disease (CHD). CHD occurs as a consequence of changes in the structure of arterial walls (atherosclerosis) and an increased tendency of the blood to clot (thrombosis). The consequence of these interactions can be blockage of the arteries supplying the heart resulting in a heart attack (myocardial infarction). CHD in particular is associated with high serum LDL and cholesterol concentrations (Castelli, 1986). Dietary regimes which reduce these factors would be expected to ameliorate the incidence of this disease. A number of prospective studies studying the subjects' diet and eventual incidence of coronary heart disease have been described Morris *et al.* (1977) found that consumption of cereal fibre but not vegetable or fruit fibre inversely correlated with CHD incidence in a group of middle aged male Londoners. A similar type of study in Zutphen showed that mortality due to CHD was four-times more likely in persons eating a low fibre as opposed to a high fibre diet (Kromhout *et al.* 1982). However this relationship disappeared when more refined statistical analyses (multivariate analysis) was used. Furthermore, no difference in fibre consumption between those who died from CHD and those who survived was observed.

5.6.7 Diabetes mellitus

Diabetes mellitus is a disease characterized by high serum glucose concentrations, brought about by reduced insulin production. There are two forms of the disease (Whitehouse, 1982): type 1 (insulin-dependent diabetes mellitus (IDDM) where there is a total lack of insulin and regular injections of insulin to maintain correct serum glucose concentrations are required; type 2 or noninsulin-dependent diabetes mellitus (NIDDM) where cells become resistant to the effects of insulin, this condition is managed by diet. Diabetes has been proposed as a fibre deficiency disease (Cleave and Campbell, 1966; Trowel, 1974). Various sources of fibre have been shown to be efficacious in dealing with this disease making the management of both types of the disease easier (reviewed by Anderson, 1986). Dietary fibre appears to exert its effects, at least to one degree or another by modifying glucose uptake into the blood stream from the small intestine leading to less abrupt changes in serum glucose and insulin concentrations.

5.6.8 Dietary fibre and obesity

Obesity has been defined as an excessive accumulation of fat in the body as a consequence of caloric intake being in excess of a person's requirements (MacNalty, 1961). Obesity is therefore linked with satiety which fibre products are known to induce (Blundel and Barley, 1987). The mechanisms by which hunger is suppressed are diverse but can be summarized under two broad headings.

Lengthened eating times. Fibre-rich foods generally require more chewing (McCance *et al.* 1953), making ingestion more laborious and slower.

Slower gastric emptying times. As detailed in section 5.4.2, high-fibre diets tend to be retained in the stomach longer with slower gastric emptying times. Di Lorenzo *et al*, 1988 have associated slower gastric emptying times with increased feelings of satiety. A further factor contributing to slower gastric emptying is the 'ileal brake' (Read *et al.* 1984), whereby nutrients which are not absorbed in the upper regions of the small intestine (jejunum) reach the lower end (ileum) and stimulate a reflex which inhibits gastric emptying. Since fibre appears to inhibit absorbtion of nutrients in the small intestine it may inhibit gastric emptying by promoting increased amounts of nutrients to activate this reflex and thereby promote satiety.

Although there is evidence that, in the short-term, dietary fibre in various forms (including wheat bran) promotes satiety and contributes to weight-loss (e.g. the 'F-plan' diet), there is little or no evidence that prolonged consumption of fibre in the absence of a controlled diet will maintain weight loss in the long-term.

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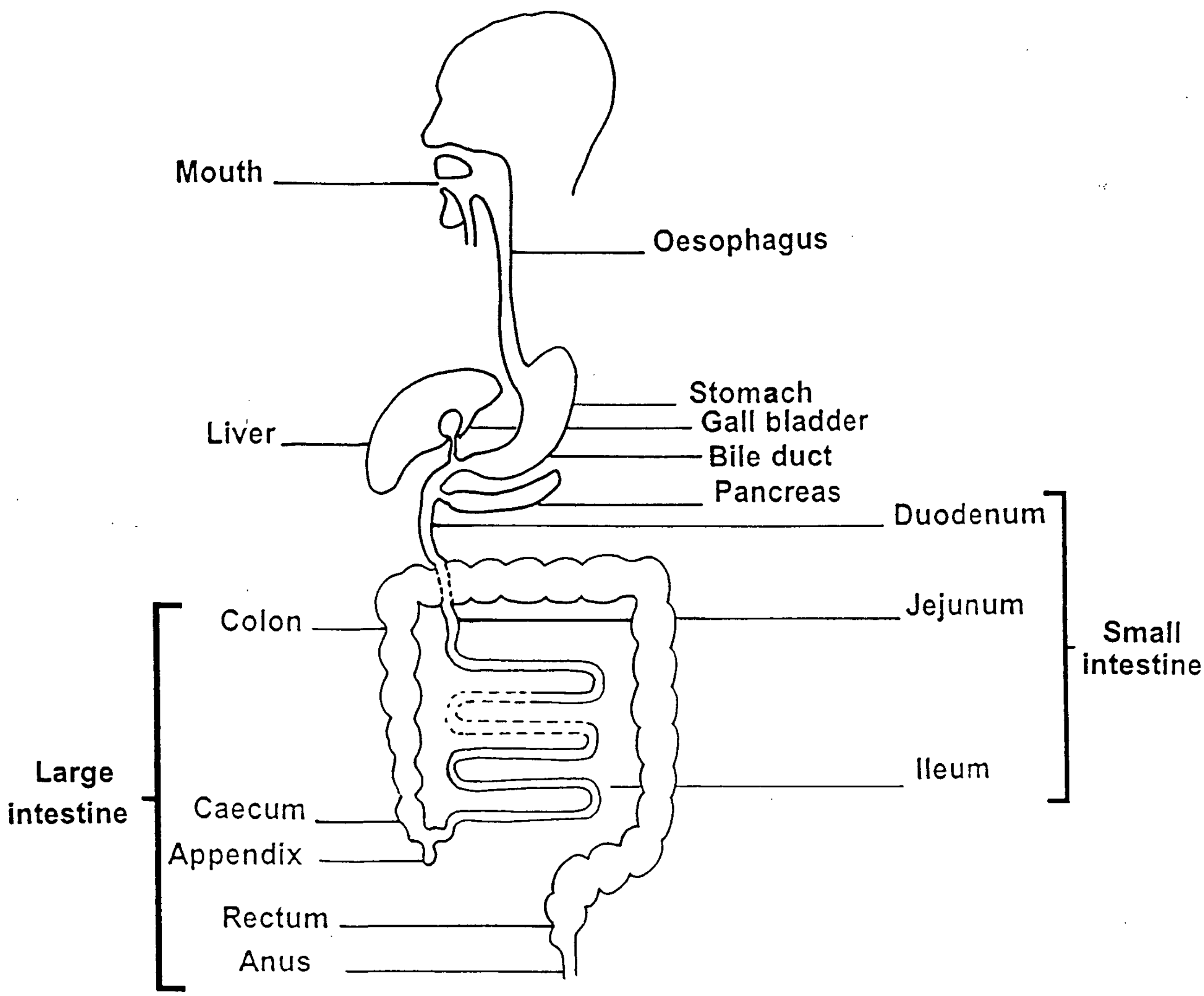
Appendix 5.1

Diagram of human alimentary canal



6. IMPLICATIONS FOR INDUSTRY AND THE CONSUMER

6.1 INTRODUCTION

From the previous chapter it becomes apparent that many of the physiological consequences of dietary fibre appear, at worse, not to be deleterious to the consumer, and many are actually beneficial e.g. in colonic diverticulosis and diabetes. This chapter will review current thinking on the role of fibre in a healthy diet, examine the uses of cereal-derived fibre in both food and non-food products, discuss the effect of the fibre message on sales and finally return to the question of 'What is fibre?' and its implications with regard to labelling and the role of resistant starch.

6.2 CURRENT RECOMMENDATIONS

Despite being incomplete, research into the physiological effects of dietary fibre has prompted both scientists and members of the public to advocate its increased consumption. A number of national governments have commissioned expert committees to review the literature and make recommendations. The general consensus is in favour of increased fibre consumption. In the United Kingdom advocacy of increased fibre consumption has been propounded throughout the last decade. Advice has included:

> 'Eat foods which are closer to natural grain, vegetable or fruit' (Royal College of Physicians, 1980).

> 'It is recommended that the intakes should be increased to an average of about 30g dietary fibre per day for adults' (National Advisory Committee on Nutrition Education (NACNE) 1983).

> 'The panel sees advantages in compensating for a reduced fat intake with increased 'fibre'-rich carbohydrates (e.g. bread, cereals, fruit and vegetables' (DHSS Committee on Medical Aspects of Foods Policy, 1984).

Similar recommendations have been made in the USA (US Department of Health, 1988). In the light of a perceived increased public concern over healthy eating, dietary fibre appears to have considerable sales potential.

6.3 DIETARY FIBRE - APPLICATIONS

Cereal based fibres are finding uses both as food materials and for other uses e.g. medicinal, in the treatment of constipation. Dietary fibre tablets (80% from cereals) have been used to treat constipation in pregnant women (Greyersen, 1986). One product marketed is 'Fibre-Form', developed by the Tricum AB Company and sold as a dietary laxative in Sweden.

Fibre sees its greatest application in the food industry and has a number of applications in particular with regard to the production of low calorie foods. Dougherty *et al.* (1988) have published recipes for low calorie breads, soft-type cookies and pastas using fibre derived from oats. Another area where fibre is playing an increasing role is the breakfast cereal market which has considerable potential for expansion (McKechnie, 1985). Advocating breakfast cereals as a source of fibre appears to pay off as evidenced by an approximately 25% increase in US sales for Kellogg's bran products from 1983 to 1985 (Maxwell, 1986).

6.4 THE SALES-POTENTIAL OF FIBRE

Throughout the Western world the public is showing an increased awareness of health and a desire for 'healthy' food. To an extent the 'fibre message' has had an effect, according to the UK National Food Surveys, consumption of 'brown, wholewheat and wholemeal bread' has risen from 4.86oz per week in 1979 to 9.19oz per week in 1986. Since then the figure has dropped slightly (8.39oz in 1987 and 8.23oz in 1988). The market share of wholemeal bread has increased from 8.8 to 15.5% for the period 1983-87 (Federation of Bakers 1989) Analysis of National Food Survey data reveals that consumers from all socio-economic groups are eating more wholemeal bread and that the greatest proportional increase in consumption is seen in socio-economic groups C and D. Other products in wholemeal form e.g. pasta have also made an appearance on supermarket shelves and many traditional cereal products have substantial fibre contents (Appendix 6.1). The fibre-boom however appears to be very limited. In the three years for which data is available (1986-1988 inclusive) consumption of fibre (as NSP) in the UK has altered very little. It is also interesting to note that consumption of dietary fat is still very high and no reduction on the scale seen in the US has been observed. The reasons for this can only be guessed but may include: a general consumer preference for white farinaceous products (historically there has been a preference for white bread); the public appear to react to things which are 'bad for them' rather than what is 'good for them', wholemeal products which require cooking (e.g. wholemeal pasta) take longer to cook and are therefore less convenient. Clearly to take better advantage of the potential of fibre, products should have conventional appearance but be fibre enriched, one such example is soft grain white bread.

6.5 SELLING THE FIBRE MESSAGE

There are two aspects to selling fibre, the first concerns labelling both with regard to general claims and nutritional content and the second is to readdress the questions: What is dietary fibre? and What role resistant starch?

6.5.1 Labelling

At the time of writing (January 1991) there are no regulations governing nutritional labelling however, the EC Directive (Commission of the European Community) of September 1990 requires member states to issue regulations enacting its provisions. Nutrition labelling in the UK is voluntary and will continue to be so under the terms of the directive. Currently two sets of guidelines have been produced by the UK Ministry of Agriculture Fisheries and Food these are:

Guidelines on Nutrition Labelling, January 1988.

Nutrition Claims in Food Labelling and Advertising. FAC (Food Advisory Committee) May 1989.

Although at the moment advisory, these guidelines will most probably form the basis of future legislation. Nutritional information can be provided in one of three formats depending on the amount and type of information to be presented:

Category I	Energy, protein, carbohydrate and fat.
Category II	Energy, protein, carbohydrate, fat with a breakdown to show the proportion of saturates.
Category III	Energy, protein, carbohydrate (with a breakdown to show sugars) fat (with a breakdown to show saturates) sodium and fibre.

From the above it is apparent that details regarding the fibre content of a particular food must be made as part of a Category III declaration.

The FAC guidelines for advertising products with regard to claims for fibre (calculated as NSP) give the following specifications. If the claim is that a food contains 'more/increased/higher' fibre then it must: have a fibre content 25% greater than that found in similar foods typical of those for which no claim is made; a total fibre content of greater than 3g per 100g or of the reasonable daily intake; a Category III nutrition declaration (see above) must be made, if the claim is made for a product whose normal serving is less than 50g or greater than 150g the declaration must include a value for a portion (serving) of specified size. Advertising claims must be substantiated in the advertisement and when sold, the product must be labelled as specified previously. Products claimed to be a 'source of fibre' must have a fibre content of at least 3g per 100g or provide 3g in a reasonable daily intake; a Category III declaration must be made, on the basis of 100g product or a reasonable daily intake, where the claim is made on the basis of reasonable daily intake an additional declaration must be made specifying the serving size. Advertising claims must be substantiated in the advertisement and when sold, the product must be labelled as specified previously. Foods 'high or rich' in fibre must have a fibre content of at least 6g per 100g of food or that the fibre content of a reasonable daily intake must be at least 6g; products naturally high in fibre should be labelled "A high fibre food", a Category III declaration must be made for 100g of the product, where the claim is made on the basis of a reasonable daily intake or serving an additional declaration for a specified serving size must be made; advertising claims must be substantiated in the advertisement and when sold, the food must be labelled in accordance with the above particulars.

Crawford (1989) has recently published a survey of compliance with these guidelines. Out of a total of 122 different bread wrappers covering a wide variety of bread types 29% made claims with regard to dietary fibre. Out of 35 labels examined only one fully complied with the guidelines, the predominant deficiency in the rest was the failure to provide a Category III declaration.

6.5.2 Defining dietary fibre and the resistant starch question

Currently, for UK labelling purposes, fibre is defined as nonstarch polysaccharides, as measured by the Englyst Method (Englyst, *et al.* 1982) and consequently ignores both lignin and resistant starch. As detailed here and elsewhere (Berry, 1987,

1988) both lignin and resistant starch enter the large intestine and are physiologically active. It can be argued therefore that current estimates for the fibre content of foods are conservative if not low. A good example of this is bread. Consideration of Table 6.1 illustrates that inclusion of lignin and resistant starch (which would be measured in the AOAC method, see 4) would lead to almost a doubling in the fibre content of white bread. If, as is likely the AOAC method is adopted by the European Community, this will have considerable impact on claims regarding dietary fibre content.

Table 6.1 Fibre content of bread
(g per 100g)

Type	**Nonstarch polysaccharide**	**lignin**	**resistant starch**	**Total**
White	1.5	0.4	0.8	2.7
brown	3.4	0.4	0.8	4.6
wholemeal	5.8	0.6	0.7	7.1

Adapted from Federation of Bakers (1989).

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Appendix 6.1 Fibre content of some typical cereal derived products

Product	Fibre content (g/100g)
Corn bran	89
Wheat bran	46
Oat bran	30.4
Wheat, wholemeal flour	11.8
Wholemeal bread	8.5
Ryebread	6.4
Brown bread	5.1
White wheat flour	3.2
White bread	2.7
All bran	30.1
Shredded wheat	13.3
Cornflakes	12.3

Adapted from Dreher, 1987.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 CONCLUSIONS

7.1.1 Definition of dietary fibre

The term dietary fibre describes a heterogenous group of (often) physiologically-active plant-derived materials (most of which are not fibrous). Their one common feature is that they are resistant to the actions of digestive enzymes produced by the human alimentary canal proper. While some workers have tried to limit the term fibre to NSP, many now consider the term to embrace NSP, lignin and resistant starch, all of which are measured as fibre in the AOAC method.

7.1.2 Chemistry of dietary fibre

Dietary fibre comprises three chemical subsets: nonstarch polysaccharides (NSP); lignin and resistant starch. It is chemically diverse and as a consequence has a combination of many different physico-chemical properties. In the case of cereals, composition of dietary-fibre depends on its genetic source and the extent to which it has been processed (e.g. milling extraction rate, method of cooking). Two methods are currently employed for determining the fibre content of foods: the AOAC method measures dietary fibre on a gravimetric basis; while the Englyst method is more specific measuring fibre in terms of NSP. The consequence of this difference in interpretation is that widely differing values for the same food-stuff can be obtained. Currently the AOAC method is used in Switzerland, USA and the Nordic countries while the Englyst method is favoured in the UK.

7.1.3 Consumption of dietary fibre

Estimating consumption of dietary fibre is made difficult by three confounding factors: seasonal variation; daily variation and dietary habit. Nevertheless it is still possible to make some estimate of fibre consumption. Fibre consumption in the Western World is much lower than that in East Africa, however the assumption that Third World countries in general enjoy a high rate of fibre consumption appears to be incorrect. Bingham (1986) has reported some areas of India with fibre consumptions similar to Western Europe. Even within countries having similar rates of fibre consumption the amount attributable to cereals can vary considerably.

7.1.4 Physical-chemistry of dietary fibre

The physical-chemistry of dietary fibre determines its physiological effect. The molecular composition, degree of chemical modification, structure and conformation of fibre determine its physical-chemical properties. Six of the properties make a major contribution to the physiological quality of dietary fibre: WBC, viscosity, cation exchange, absorption, capacity to be degraded by the gut microflora and particle size.

7.1.5 Dietary fibre and gut function

Dietary fibre modifies a number of aspects associated with gut physiology. These include increasing transit time within certain sections of the alimentary canal although paradoxically shortening overall mouth-to-anus transit time (due to its effects on the large intestine). This effect has consequences both with regard to nutrient absorption and the incidence of various gut disorders. Independently of gut motility, dietary fibre also modifies absorption of nutrients by other means including the reduction of luminal mixing and acting as an adsorption matrix. Dietary fibre also modifies the biochemistry of the gut microflora.

7.1.6 Dietary fibre and disease

There is now strong evidence that dietary fibre, in particular that from cereals, has a palliative effect on a number of diseases including constipation, diverticular disease, irritable bowel syndrome, diabetes mellitus and obesity. Furthermore, different types of dietary fibre modify cholesterol metabolism in different ways. The results of these interactions are beneficial changes in predictors of risk to both gallstones and CHD. However, definitive epidemiological evidence for dietary fibre having a preventitive role in these diseases is lacking. Although in some diseases (e.g. diverticular disease) the beneficial effect may be due to fibre **per se**, in others the effects might be secondary, reflecting shifts from high-fat, meat orientated diets to low-fat vegetable-orientated ones. A beneficial role for dietary fibre in the incidence of colo-rectal cancer remains unproven. Hypotheses based on earlier epidemiological studies remain unsubstantiated and the absence of a satisfactory animal model has resulted in ambiguous data being produced.

Interest in dietary fibre was originally prompted, by among other things, the observation that the incidence of a number of diseases common in the West (e.g. CHD and colerectal cancer were rare in the Third World (East Africa) where large amounts of dietary fibre are eaten. Over the last 20 years, research has failed to demonstrate that these diseases are fibre-deficiency syndromes, similar for example to scurvy (caused by vitamin C deficiency). The aetiologies of CHD, colorectal cancer and the other diseases discussed here are far more complicated and the

Western life-style contains many factors which contribute to the risk of these diseases. Present scientific knowledge is such that it is unjustified to claim that failing to eat sufficient dietary fibre leads to increased risk of disease. However, there is evidence to advise that eating increased amounts of dietary fibre may contribute to a reduction in risk and, in some cases, actively assist in the management of, and recovery from certain clinical conditions.

7.1.7 The selling of dietary fibre

Numerous advisory bodies have advocated increased dietary fibre consumption. Increased awareness to the health consequences of various dietary practices has led to the development of a discriminating public. Production of food items rich in dietary fibre will have a sales premium. Manufacturers will have to take due note of the necessary legislation concerning the labelling and marketing of such products.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

7.2.1 Definition and analysis of dietary fibre

A unifying definition of dietary fibre which permits simple laboratory analysis for nutritional requirements is required. In the light of research showing that both lignin and resistant starch are biologically active, simply referring to dietary fibre as NSP (as measured in the Englyst method) is too restrictive. One possible definition is: plant polysaccharides and lignin resistant to digestion by enzymes secreted by the alimentary canal. Such a definition would include resistant starch and embraces all that is detected by the AOAC method.

7.2.2 Predicting the physiological effect of dietary fibre

A great deal of information is now available on how the various physiological properties of dietary fibre are dependent on its physico-chemcial properties. Research should be directed at developing and refining assays (both *in vivo* and *in vitro* which are predictive of physiological function. Recent work by Adiotomre *et al* (1990), who have developed *in vitro* assays for measuring such factors as the effect of fibre on glucose uptake and faecal bulk, provides the foundation of how this work should proceed.

7.2.3. Effect of cooking on the amount, composition and physiological function of dietary fibre

One of the limitations of most current research has been the use of single fibre-sources and in an unprocessed form. Research is needed to investigate the effects of cooking and other forms of processing (e.g. extrusion) on fibre content and physiological activity.

7.2.4 Dietary fibre and disease

Early enthusiasm for the idea that a number of diseases common to the First but not the Third Worlds were caused by fibre deficiency has proved to be unjustified. Subsequent studies (e.g. Bingham, 1986) have shown that many Third World populations with low incidences of these diseases eat a similar proportion of fibre in their diet as found in the west. Notwithstanding the above, dietary fibre has been shown to have palliative effects on a number of diseases particularly those of the gut and diabetes mellitus. The role of dietary fibre in two diseases, CHD and colon cancer is still speculative. These two diseases are major causes of death in persons who have not reached old-age. Consequently they are a severe drain on national health-care resources and major causes of emotional distress. The role of dietary fibre in the incidence of these two diseases needs to be more rigorously investigated. Questions which should be addressed include: does fibre have a protective effect on all sectors of the community, or only on subsets (e.g. does fibre exert an effect only in persons with extreme hypercholesterolaemia - CHD, or has fibre a protective effect for people at risk of familial adenomentous polyposis - a subset of the population with a genetic predisposition to colon cancer). Intervention studies (i.e. comparing groups of people on different diets over many years) are impractical (bearing in mind the sizes of groups and lengths of time required) and research will have to involve the use of improved animal models or identifying markers in humans, predictive of altered risk. In the performance of human-based studies particularly, great care will be needed in demonstrating that any effect observed is due to additional consumption of fibre, rather than reduced consumption of another risk-factor.

7.3. REFERENCES

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