The Impact of Food structure on Taste and Digestibility

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The Impact of Food Structure on Taste and Digestibility

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The modern food chain depends on complex interactions between businesses from farming to retail. Until recently their success depended upon providing consumers with safe, convenient food which was pleasant to eat, at a reasonable value for money. This has required detailed research into how food structures deliver recognisable and preferred types of foods, from hard solids to thick liquids. Fortunately the consumer is able to detect and report sensations of texture and flavour which can be related to the composition, structure and breakdown of food in the mouth. Chemists, physicists and engineers can attempt to build mechanistic models of how structures relate to perception. The state of the art in our understanding and design capabilities are reviewed. In the developed world, the success is self evident as food prices (as a proportion of income) have decreased and there is a surfeit of choice on the supermarket shelf.

More recently, the requirement to add a balanced healthy diet to the simple pleasure of eating has become the new target. This is a different type of challenge. The effects of diet on health are long term, and not easily reported by the consumer. Whilst we know something of how the digestive tract works in breaking down foods, we know little of how food structure impacts upon this process, and even less of how the neural and metabolic feedback systems operate to relate food structures to satiety and satiation. Therefore, in the absence of causal models relating structures to eating habits, structures designed to achieve both immediate pleasure and long term healthy eating are much more speculative. What we think we know, and what we need to know are reviewed. There is no doubt that other skills, in nutrition, physiology, neuroscience, and molecular biology etc. will need to be added to the classical approaches of food materials science and engineering if these challenges are to be met.

1. The structures of food

As hunter gatherers, we learned to eat biological materials, whose structures comprise assemblies of animal and plant cells. We chose those that can be eaten raw (i.e. broken by simple mouth action). The advent of fire allowed these and others to be cooked, extending the range of edible material, and setting Homo sapiens apart from the great apes. This “paleo” diet is now presented in popular literature (1). Its benefits are purported to be “*natural*”, yet all the components are available at the local supermarket. Our modern food chain primarily provides *convenience.*

The discovery that grain could be stored for months, and processed into aerated structures which are then chewable, is the basis of arable farming and the bakery business; and allowed rapid human population growth, because the raw materials and some products can be stored, and remove the risks of starvation. Likewise , the recognition that certain organisms were not harmful, but provided safer, longer life food gave us cheese, yoghurt, miso, tempeh, beer, wine etc. Even the offcuts of meat and fish are reformed into salami, surimi etc.. These *fabricated* structures are manmade, developed empirically, but have one thing in common. They can be broken in the mouth, chewed and swallowed.
The success of the modern food ingredient and manufacturing industries has been to convert small scale domestic processes to automated factory production at a large industrial scale. These *fabricated* foods cannot exist without a manufacturing industry of some kind, and the ingredients to build the structures. Our modern food chain provides *variety, choice and value for money*. (Fig1)
The processing needed to provide safe and palatable foods was developed empirically, but the original craft skills are highly prized, and have needed to be reproduced at large scale to maintain recognisable eating quality. Such foods produced by the same methods and at a small scale are regarded as “traditional”, often protected by “Region d’origine”, or “appellation controlee” legislation. We can eat them, their tastes are recognisable, but the chemistry and physics involved is extraordinarily complex. Our modern food chain protects this *quality.*

Innovation did not stop there. The sheer pleasure of eating has driven the development of indulgent foods like confectionery, Ice cream, dressings and desserts, all of which have complex structures at the micro and ultrastructural levels

To reduce costs and increase volumes, the economies of scale available from large scale processing have been adopted. Now we need to understand how materials and processes interact to form these acceptable structures and tastes, and how, as consumers, we recognise food types and their quality. This requires an understanding of how food structures form in processing, where we share the science and engineering of many other industries. However, the targets for food are very different. We must be one of the few industries where successful structures must break, and in a sequence recognisably related to preferred "Natural" and "Traditional" foods. Clearly success has been achieved since in the developed world our supermarkets contain a plethora of food types and their cost, relative to personal income has decreased. Our modern food industry must provide *value for money in the eating process.* This has been achieved largely empirically by copying existing product structures, and upscaling kitchen processes but at the same time we have begun to understand the oral breakdown process, where the consumers' quality judgements are made (2). The initial impetus for this kind of investigation was provided in the 1970's, when shortfalls in muscle tissue foods were predicted. Analogues were manufactured from novel raw materials, but whilst they looked like meat, their texture and flavour were not generally acceptable and better understanding of the causal connections between structure breakdown and in mouth texture perception were required.

2. The process of mastication

If we treat eating as a physical process of breaking and reassembling food, we need to know how the machine called the mouth works. Like any other process engineering study, we can observe the machine in action, (by X-ray and MRI video), and take food samples from it. This has been done with many food types (3,4). What we observe is a process common to all solid foods. Firstly the bitten portion is size reduced, but then reassembled with saliva to form a swallowable material. (Figs 2 and 3)

The textural difference between foods appears to be related to the fracture pathway of the initial food, its impact on saliva stimulation and the speed at which it becomes swallowable. This led to the proposition of a Breakdown Pathway for every food, which defines its unique textural quality (5). (Fig4).

The details of fracture can be examined from chewed samples, where differences in the fracture of different food types becomes obvious, and begins to identify the role of components as points of weakness (fat droplets in baked goods), and strength (connective tissue in meat, cell walls in plants). Manipulating these by processing or building the appropriate product architecture should allow the design of preferred structures, but what should we change? Fortunately, in human subjects, our mouth machine is connected to an intelligent and articulate computer and can verbally report the properties it senses during the mastication process. We immediately learn that whilst chewing is largely a scripted process, we are all capable of detecting small differences at many stages of the breakdown path of any food. (Fig5). Furthermore, preference for any particular type of food can be related to its proximity to the swallowable state. Thus, while we expect to chew meat, if we have to do too much work of fracture it is regarded as "tough". A cake may break easily, but if it requires much saliva to lubricate before swallowing it is "dry". It appears also, that if saliva stimulating tastants and flavours are released throughout the chewing process, preference will be heightened further. Perhaps the best examples are fresh fruits and vegetables, where the turgor pressure within cells causes brittle fracture of the walls, and each chew breaks further cells, releasing lubricating liquid, sweet taste and recognisable flavour. Fig6. The success of the modern food industry is that by accident and design it provides *hedonism, pleasure by the mouthful.* This brings us to the next problem.

3. The processes of digestion.

There is no doubt that overweight, obesity and other medical symptoms classified within the Metabolic Syndrome have increased in the developed world, and do so whenever food supplies become rich and varied. The media blames the food industry for introducing "unhealthy" foods with high sugar, fat and salt, while dieticians and medical practitioners at least recognise that it is diet and lifestyle rather than particular foods that need to be rebalanced. Nonetheless, having focussed on hedonics to achieve market success, the food industry is aware that this will not be enough in future. There are several actions that it will need to be taken, and since consumers are reluctant to accept radically new sensory textures, the control of food structure will be a rate- limiting step. Unfortunately, the process of digestion is even more difficult to measure in vivo than the mastication process, and the consumer is not able to respond verbally to changes in food structures occurring in their lower alimentary canal. A recent review of gastric digestion has set the scene (6). Progress will be difficult and slow, and requires a deep understanding of the kinetics of release of signalling molecules, their feedback to the brain and the subsequent metabolic regulation within the gut. Nonetheless, several approaches are underway (7).

Reformulation

Nutrient values of food components are well known and tabulated. The substitution or elimination of a calorifically dense ingredient is an obvious step. But we have shown that the hedonic value, and therefore the structural breakdown of the redesigned food must stay much the same, and the cost must also remain similar.

Fat reduction and replacement has been successful by designing other components that fulfil its function via their structure (e.g. gelled water in spreads, mayonnaise and dressings). Such products have an additional nutritional benefit if the water structurant is a soluble fibre of low calorific value, rather than a calorific starch. Also, the desirable property of “creaminess” usually associated with high fat products, may not be a property only of fat. Rather, any small soft stable particles may provide a similar sensation, and might explain why the small protein aggregates in yoghurt, and even very small stable air bubbles in ice cream may impart the same sensation.

The replacement of fats in baked goods is more difficult since the structural function in many bakery products is to “shorten “ the texture by providing weak points in the baked structure, and separate layers of dough from one another. This requires not only a phase which is incompatible with the hydrophilic dough such as a triglyceride (oil), but also must have a rheology suitable for layering. This is provided by a partially crystalline fat. All of these functions may be delivered by sucrose polyesters, with similar melting characteristics to triglycerides, but these tend to be regarded as “unnatural” chemicals.

The same requirement for a particular melting behaviour is vital in chocolate confectionery. The indulgent quality of chocolate is expressed in the architecture of its fat structure and its temperature sensitivity. Whilst legal definitions of the composition limit reformulation, this will not prevent clever redesign of structures to give a “chocolate-like” texture and taste at a lowered calorie level (8).

Recently, arguments are presented that it is sugar metabolism, rather than fat, which is the dominant cause of metabolic syndrome and obesity (9). Therefore, simple sugars and rapidly digestible carbohydrate intake should be the focus for calorie reduction. There is even evidence suggesting that obesity is related to the reduced response of opioid sensors in the brain (10), though whether this is an inherited trait, or has been induced by excessive sugar intake is not clear. Sweetness can be replaced by non metabolisable sugars (erythritol) and naturally sweet molecules (stevia). However, in many products, the problem for the reformulator is to match the properties of sugar solutions and glasses derived from them.

Salt levels are also linked to long term health. Salt is a ubiquitous taste enhancer and it is a fact that many foods currently contain more salt than appears necessary to produce the taste sensation required. However, like soluble small sugars, it is also a highly functional ingredient, modifying the swelling and solubility of most biopolymers. Protein globulins dissolve or swell in salt solutions, and this is a requirement for structures where proteins are a major structural component (meat and fish sausage; cereal doughs, baked goods and extrudates; foams and emulsions). Other monovalent cations produce a similar effect, but sodium cannot be completely removed or replaced. Its optimal operation as a taste enhancer can be achieved by ensuring that sufficient reaches the taste buds during the chewing process.

In lower water activity foods, as well as controlling microbial growth, sugar and salt determine the swelling, solubility and the glass transitions of other polymers. These must remain similar if processing, product architecture and sensory textures are to be maintained. Otherwise novel process control or even new processes will be necessary, causing an inevitable increase in capital costs and factory redesign.

Understanding and controlling calorie intake, including satiation and satiety

It is not surprising that our preferences for foods appear linked to their calorific value. We like the sweet taste of sugar and the creamy sensation of high fat foods, however we cannot measure calorie intake directly whilst we are eating. Dietary advice based on calorific value relies on calculations from the composition of any foodstuff and little account is taken of its macro or microstructure. Several studies have indicated that true digestibility is reduced by the macro and microstructure of foods, for example by “encapsulation” of nutrients by cell walls (11), but little data is available.

Why do we start and stop eating? This is a complex problem of physiology and neural signalling that has yet to be mechanistically linked to food structure and composition, though recently work is expanding rapidly as diet and health become medical issues. A recent review suggests that sensory properties in the mouth may give expectation of satiety and thereby influence appetite (12).The food industry watches these developments with interest, and will respond rapidly if reformulation of individual foods can be shown to have an effect on appetite.

We know that hormones such as leptins, ghrelins, cholecystokinin (CCK), glucagon-like peptide (GLP1), and pancreatic peptideYY are involved in the sensations of hunger and satiety, and are up and down regulated during food digestion (13). It appears that nutrient content in the stomach can initiate the signalling process (14), but available nutrient levels will themselves be influenced by digestibility and food structure. During eating, short term satiation is signalled by mechanosensors measuring stomach extension, and this together with stomach transit can be measured by imaging techniques (15). As expected, hydrocolloids (soluble and insoluble fibre) which gel and thicken but are not metabolised in the stomach or small intestine can slow this process. With prolonged controlled diets, some weight loss is obtained (16), but for a single meal the satiation is transient, and we all know from personal experience that the response of the pleasure centres in the brain can even override the discomfort of stomach distension. We continue to eat when we already feel “full”, and it is reported that there may be phenotypic variations in the human population which determine the extent to which we respond to satiety signals.

Whole body measurements of calorific intake suggest that, whilst high fibre foods are satiating and of lower calorific value, over time the total calorie load is adjusted back to the same value in ad libitum feeding (17). This highlights the difference between short term satiation and longer term satiety.

There are effects of food structure which appear to have effects on satiety. Surprisingly, increasing the chewing time or number of chews required to eat a meal appears to reduce the intake of subsequent meals by as much as 15% (18). This appears to be related to the food type. However, as explained above, making foods which require more chewing will make them less preferred, unless the prolonged process is itself made more pleasurable by enhanced flavour release or lubrication. Therefore, this effect is probably more easily implemented by changing the overall diet and habituation of human subjects.

High protein foods appear to deliver prolonged satiety. The effect was first noted with dairy ingredients, but now appears to be via the action of peptides derived from most protein sources, (19). A plausible mechanism relating active peptides to gluconeogenesis and prolonged satiety signalling has been proposed, (20). This means that structures where fat and sugars can be replaced by protein, should have a multiple advantage via total calorie reduction, reduced glycaemic index AND prolonged satiety.

We observe that the demand for animal protein is rising in the developing world, where consumers are rich enough to afford it. However, current production methods appear unsustainable. The challenge will be to meet consumers' sensory preference from alternative protein sources, and this will certainly mean restructuring novel materials. Achieving a nutritional benefit, whilst providing acceptable oral breakdown, remains a considerable challenge to materials science and processing and cannot be achieved just by changes in composition.

Neither can we be entirely sure that deleterious side effects of proteins are minimised. We do not yet properly understand how allergic responses are initiated and controlled, and the generation of toxic peptides in the hindgut is reported but its significance is not yet understood.

Delivering molecular actives.

It is becoming apparent from epidemiological studies, that micronutrients from food can have positive protective benefits for human health against non communicable diseases such as cancers, heart disease etc. The best worked examples are vitamins whose molecular structure and metabolic effects are well known. Only small amounts are necessary, and fortification of foods with added actives is relatively easy provided the molecular activity is protected against processing damage, and provided we know what the active species is. The search for other agents is ongoing, both by the food and pharmaceutical industries, since the latter see the possibility of new business from the demonstration of protective actives. Quite rightly, legislators require the demonstration of clinical efficacy before health claims can be made.

Fortification by the addition of actives (food industry), or new "vitamin pills" (pharmaceutical industry) are probable options. Consumers would prefer their food to be both health protective (Functional) but with minimal processing (Natural).This is an enormous challenge, since the benefit needs to be provided by a recognisable food structure via the release of an as yet unidentified active, at the right place and at the right time in the digestive tract. This will require collaboration of primary food producers, processors, experts in human physiology and nutrition to prove efficacy and value. All this to be done in the context of food, which must remain cheap, recognisable and easily available.

Nonetheless it will be done. A working example is the development of a new broccoli, with a higher than usual level of glucoraphanin which is converted to the biologically active sulforaphane. This latter molecule has demonstrable activity in human metabolism by suppression of cytochrome P450 enzymes, induction of apoptotic pathways, suppression of cell cycle progression, inhibition of angiogenesis and anti-inflammatory activity, (21). It remains to be seen whether prolonged feeding trials produce the predicted beneficial health effects, when the active is delivered during the structural breakdown of vegetable cells in the human digestive tract. Manufacturers and retailers will not wait for scientific proof, and a new broccoli is already on supermarket shelves (22).

Conclusions

Most of the food we eat has a macro, micro and ultrastructural architecture. Food materials science and engineering has traditionally focussed on the conversion of raw materials to finished foods. Its success has been to bring enormous variety and pleasure to the consumer at a reasonable cost, by understanding how structures break down and interact with the mouth and nose. In future the challenge is to do the same, using novel materials to deliver a similar hedonic response but with a greater health focus. This will require a much better understanding of the behaviour of foods in the entire human digestive tract, their structural breakdown and the delivery of nutrients at the right level, in the right place, and at the right time. Though we are far from achieving this at present, new measurement science and collaboration with all the disciplines of human biology are beginning. Food has always been important, but the future for its research has never been more exciting.

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Figures

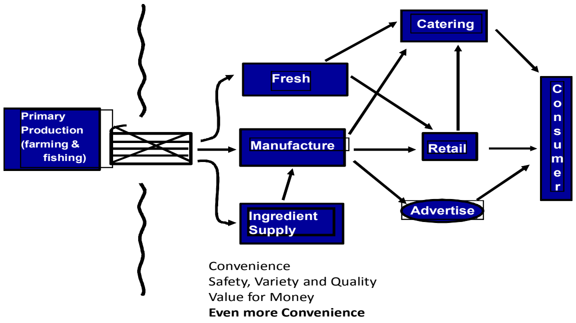

Fig.1 The Modern Food Chain (from ref.3 with permission)

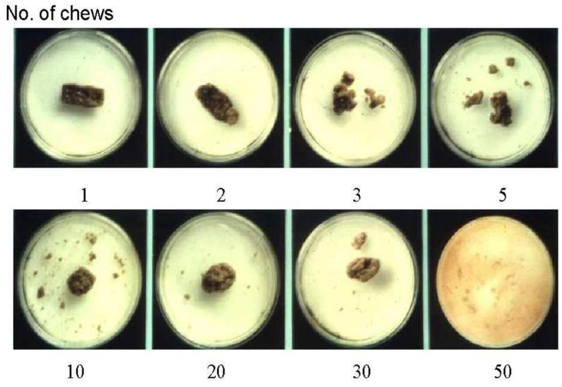

Fig.2. Chewed structures from meat pieces (from ref.3 with permission)

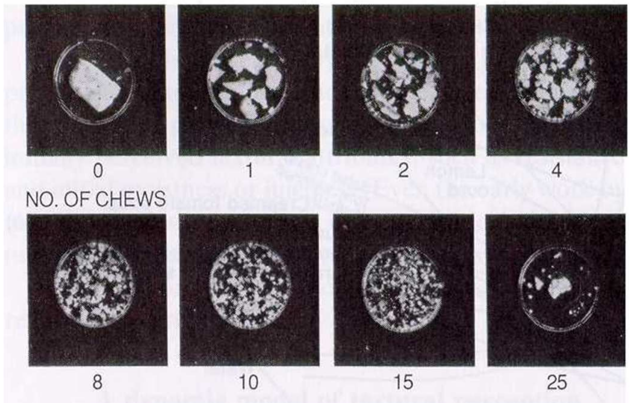

Fig3. Chewed structures from Dry Biscuit (from ref.3 with permission)

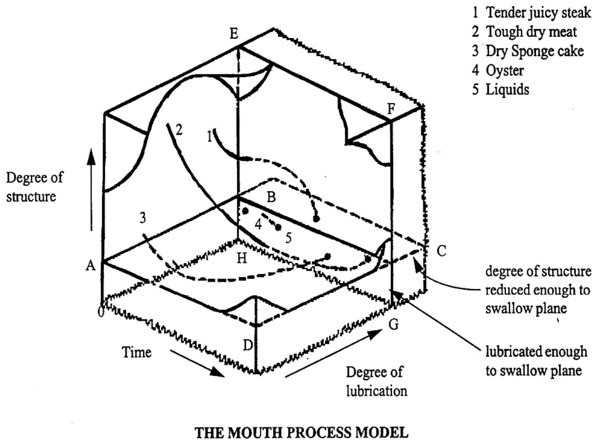

Fig 4. The Breakdown Path (from ref.5 with permission)

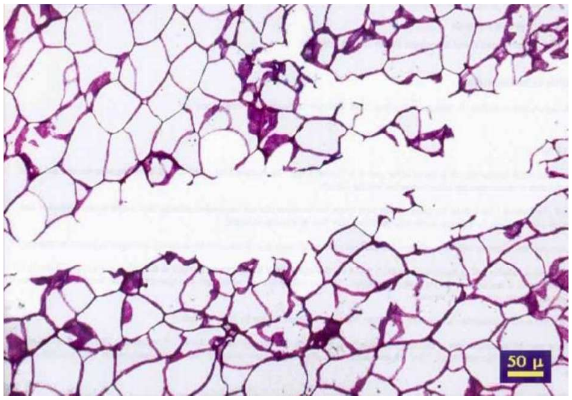

Fig 6, Cell fracture of crisp carrots (from ref.3 with permission)

Initial impression →	**Initial breakdown** →	**Ball formation** →	**Secondary breakdown**
Heaviness	*Moistness I*	*Ease of ball formation*	*Time to paste*
Resilience	*Initial crumbliness*	*Density of ball*	*Particulateness*
Firmness	*Rate of breakdown*	*Stickiness of ball*	*Final particle size*
	Particle size	*Moistness II*	*Moistness III*
	Particle roughness		*Ease of clearance*
	Stickiness		

Fig 5. Sensory descriptors during chewing cake (from ref.3 with permission)