6 The Physics of Eating

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6.1 INTRODUCTION

Whilst eating is a self-evident requirement for activity and life, the need to study the physics of the process itself is less obvious. We can all eat, there is a plethora of edible food, so who needs to know about the mechanics and physics of mastication and consumption? In fact, the interest is common to a wide variety of disciplines. Dentists need to know why teeth break and wear. Biologists and ecologists study how life forms adapt their masticatory processes to available food sources. Food scientists need to know how the development of new products and processes will be recognised during chewing, and most recently, the emergence of an ageing population, who in extreme cases have lost the dentition, muscular facilities of chewing and the ability to swallow normally, means that nutritionists now identify not only with the composition of foodstuff, but also with the processing in the mouth which determines consumption. The topic is therefore multidisciplinary in its approach, but research studies are scattered widely throughout the literature, and it is rarely synthesised into a comprehensive body of knowledge. An earlier attempt to do this can be found in *Feeding and the Texture of Food* (Vincent and Lillford, 1991). More recently, an international symposium of scientists from relevant disciplines was convened, which covered the rapidly expanding range of studies now in progress (Food Oral Processing, 2010). This chapter will not be able to complete this synthesis, but instead will update what we have learned in more recent studies, and identify to the reader other sources that contain useful and interesting information. The focus of this work will be the human masticatory process, its connection to the food we eat, and how we interpret these stimuli into a sensory response known as “texture”.

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We can be sure that to provide any nutrition at all, food must be swallowed and its size reduction, lubrication and reassembly to a swallowable state are the mechanical objectives of chewing. Since the mechanical strength of foods is different, the chewing process will have to adapt to the physical properties of the food. This requires that the human subject gathers data from mechanoreceptors in the mouth. These signals are interpreted in the brain, to provide muscle action, tongue movement and swallowing. During this processing, we perceive mechanical properties, and their combined effects are described as texture. This idea that texture is not a simple property of a foodstuff, but relates to all of the properties sensed during the entire process was generalised as a model of food mastication (see Fig. 6.1; Hutchings and Lillford, 1988).

Furthermore, different food types have wholly different breakdown paths, and require different combinations of chewing and salivation, so that any food type has its peculiar breakdown pathway. The critical processes were proposed to be the forces and work done in breaking down the food, the simultaneous release of liquid, or the uptake of saliva, during the creation of a swallowable bolus and the time taken to execute these events. These generalisations appear to be valid, and more recent work on the breakdown path of particular foods will be described later.

To understand these physical processes, we can regard chewing as a "unit operation" in engineering terms. Further analysis will require knowledge of the machinery performing the process, its control mechanisms and the mechanical properties of the materials which are to be processed. All of this information can be obtained experimentally by classical engineering approaches which examine the process directly.

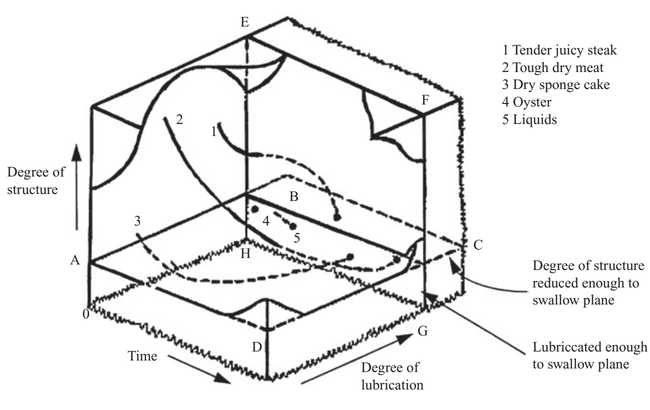

Fig. 6.1 The breakdown path of foods in the mouth. Reproduced with permission from Lillford (2000) The materials science of eating and food breakdown. *MRS Bulletin* 25(12), 38–43. Cambridge University Press.

In addition, the machine is attached to an individual who can give direct readout (in words) of their sensations during the process. Converting this qualitative verbal information into quantitative measurement of physical parameters is the basis of sensory science, where the foodstuff provides the Stimuli, and the texture perception is the accumulated response (Szcsesniak *et al.*, 1963).

6.2 CHEWING, SWALLOWING AND THE MACHINERY OF THE MOUTH: A MECHANICAL ENGINEERING APPROACH

6.2.1 Mechanical components

Fig. 6.2 shows an MRI image of a typical human head. This saggittal section shows the processing device that we have to consider.

In engineering terms, we have a combined comminuter and mixer, capable of motion in three dimensions. The teeth provide hard surfaces capable of cutting, crushing and grinding. The cavity is not large, and

Fig. 6.2 Magnetic resonance saggittal scan of the human head.

largely filled with a flexible mixing device (the tongue) which can also move in three dimensions, at variable speeds and with continuously changing shape. What is not obvious in this image is that liquid flow (from salivary glands) can be regulated rapidly and in response to chemical signals from the food itself. The tongue mixes these liquids with the subdivided food and finally despatches the chewed food down the throat to the stomach. We need information about the processing elements of the machine.

6.2.1.1 *The teeth*

Now we can call in engineers, dentists and anthropologists for advice.

The shape of teeth is important. Any mouthful of a solid or soft food must be size reduced before swallowing. Thus, whilst the small deformation properties of the intact food may be significant in the first bite, if it cannot be broken or subdivided, it is unlikely that the food can be swallowed. Therefore, it is the fracture and failure properties of foods that are the major determinant during eating. Two physical properties will be critical, namely the breaking stress (forces or loads) and the breaking strain (the extent of deformation of the specimen). Atkins' (2009) recent treatise on cutting examines tools most appropriate to deal with various materials, including teeth.

In summary, the most efficient devices to fracture high-strain materials, such as raw meat, will have the geometry of scissors or a guillotine. Carnivores show large canines for seizing and tearing lumps from their prey, but scissor-like molars to size reduce the tissue. Primates do not show this configuration, since as herbivores their diet consists of soft, weak structures (leaves and fruit), or hard but brittle materials (nuts and seeds) with low strain but high stresses at break. Crushing and grinding structures are adequate to size reduce these materials. The match between suitable food types and the dentition evolved by primates shows intriguing correlations (Lucas and Corlett, 1991).

Humans can generate high forces by action of the molars: up to 15 kg loads are recorded by most healthy dentate individuals. Since this acts on the small area between the teeth, the stress (force/unit area) is quite sufficient to break raw fruits, vegetables and softer nuts. Hard grains and thick-walled nuts are stronger than the teeth themselves. In this respect, modern humans have remained much the same as their prehistoric forbears (Leakey, 1981).

What we lack in dentition has been replaced by ingenuity. *Homo sapiens* earliest demonstrations of tool-making relate to implements designed to increase the range of edible materials. Thus, spears and knives replace our inadequate dentition as carnivores, and grinding allows hard grains and nuts to be size reduced. Indeed the key difference between man and other primates relates to our developed technology of food processing. As well as mechanical action, the other processes we have developed are the use of fire and water. These reduce the breaking strain of muscle tissue (roasting and boiling), and enhance the action of water on ground, hard materials (manufacturing soups and gruels; dough formation and baking).

6.2.1.2 *Saliva*

Now we need input from physiologists, biologists and the new “ohmic” technologies.

“Mouthwatering” is a commonly described property of food, but saliva is far from a simple solvent like water, and its variable composition is now a topic for the advanced sciences of glycoprotein biology and proteomics (Gonzales-Begne *et al*., 2011; Castagnola *et al*., 2012). The mouth is continually coated by this liquid, produced by three main glands, and hundreds of minor glands distributed throughout the oral cavity. The largest is the parotid at the rear of the mouth. The submandibular glands, at the front and below the lower jaw, produce the majority of saliva (70%); and the sublingual glands, produce about 5%, in the resting state.

However, the composition of the saliva produced by the glands is different, with the submandibular, sublingual and minor glands producing mucus, a complex mixture of glycoproteins; whilst the parotid and submandibular produce large amounts of amylase. The amount of saliva produced at rest varies with the individual, their age, state of health and the time of day, but the production rate is increased significantly by the act of chewing and the presence of weak acids (e.g. citric) in the foods consumed. For dry foods, the production of saliva dominates our ability to swallow and can be limiting for the elderly. A more complete review can be found in de Almeida *et al*. (2008).

Notice also that there are connecting passageways from the mouth to the nose, and that gas (volatile aroma) is pumped to the olfactory sensors which in turn can promote changes in saliva release and in its chemical composition.

Despite the differences in amount and composition of saliva, human subjects are capable of agreeing on the differences in the moistness and dryness of foods as different as high-moisture meats and low-moisture baked cereal products. This implies that our judgements are made relative to some internal reference state of our individual mouth lubrication, which has yet to be defined.

6.2.1.3 *Swallowing*

The process of swallowing is studied by physiologists, particularly since the incidence of dysphagia is increasing as the population ages. In normal subjects, a wide variation in food types can be swallowed, and the properties of the boluses have been characterised in terms of their viscosity (Clavé *et al*., 2006). This characterisation is probably inadequate since many boli are soft solids rather than Newtonian liquids, and the implications of complex rheology on mouth action will be discussed later. Nonetheless, the implication is that for healthy individuals there is no single "swallowable state", and the mouth is capable of adjusting its mechanical action to cope with a range of materials.

6.2.2 The process control mechanisms

This "engine" is far more complex than most man-made processing devices, not only because of its geometric complexity, but also because it is lined with chemical and mechanosensors that provide feedback and feedforward regulation of its action. It is no surprise that a complete mechanical or *in-silico* representation of mouth action has yet been achieved. In this survey, the focus will be on the mechanical operations that lead to swallowable food, bearing in mind that chemical modification occurs concurrently.

The mouth is equipped with a set of mechanosensors under the teeth and throughout the soft palate (Heath, 1991; Trulsson and Essick, 2010). These provide us with the ability to sense size, shape, hardness etc. of food and the fragments produced during chewing. These are the *stimuli* provided by the foodstuff during its breakdown. Our *response* is to modulate chewing action by varying strain, stress and their time derivatives, in three dimensions. The foodstuff, under the mechanical action of chewing plus the action of aroma and taste chemicals, provides the *stimuli* for the *response* of salivation, and hence lubrication and swallowing.

How these primary responses are then assembled in the brain to produce an integrated response described as food texture is not understood, but the advances in functional magnetic resonance imaging (fMRI) begin to throw some light on the subject (Rolls, 2011).

6.2.2.1 *Machine/motion analysis*

Because their task is to repair or maintain the function of chewing by human subjects, dentists have led the way in studying the action of the mouth and teeth during mastication. The various methods of monitoring jaw movement were reviewed by Heath (1991). The complexity of motion and the ability to use feedforward and feedback control is well exemplified throughout the chewing sequence. In particular, the response to the mechanical properties of the food itself is a dominant feature throughout, so it should be no surprise that our judgements on the texture of materials are based on measurements of the total breakdown and reassembly process. Heath also reported the differences in mouth action when confronted with a novel food, compared with a more familiar material.

Many attempts have been made to measure the effect on eating by intercepting the control signals sent by mechanosensors to the brain. One of the earliest was described as an "edometer" (Bellisle *et al*., 2000) consisting of a device capable of detecting signals from a strain gauge attached to the cheek, by which chewing strokes were measured, and a pressure sensor on the throat to detect swallowing action. For a single food type (cocktail sandwiches) the results from 10 normal healthy individuals showed remarkable consistency. Each mouthful was chewed between 17 and 19 times with a chewing rate of around 1.3 strokes per second. To remove the discomfort of the instrumentation, the results were compared with video recordings. This proved unsuccessful, but in a recent study (Ioakimidis *et al*., 2011) where chewing action was measured by magnetic tracking, agreement was achieved and an average of 15 chews per bite and swallow was identified. The actual work done during chewing cannot be identified from these studies, but Bellisle *et al*. (2000) identified that chewing behaviour was influenced by the amount of food consumed and its mechanical properties. Additionally, the palatability or preference for the food type, and the hunger state of subjects show effects on chewing. This serves as a warning to sensory analysts, requiring that careful screening and control of panellists must be employed if consistent results are to be obtained. Results also suggested that the rate and total intake of food during *ad libitum* eating varies and is greatly influenced by palatability. This has intriguing implications on consumption and may relate to weight gain, but will not be followed further in this chapter.

More sophisticated tracking of muscle action is now performed by electromyography (González *et al*., 2004). The electrical output of facio-cranial muscles is measured directly, giving not only the rates of chewing and swallowing, but also some indication of the forces generated by the muscles, and the work done in comminuting and mixing foods (Mioche and Martin, 1998). A correlation was found between food mechanical properties and mouth action, softer foods requiring less work, as expected.

The next step is to relate these chewing actions to the verbal expression of mechanical attributes by trained subjects. Some success has been achieved (Kilcast and Eves, 1991; González *et al*., 2004), but the variability of individual chewing means that the averaging of electromyographic signals from a number of panellists requires complex data analysis. In this author's opinion, there is no advantage in replacing verbal responses with myography, since human subjects can be trained to become just as efficient a measuring device by verbalising their responses to the events during chewing and swallowing. Where the significance of different material properties on texture perception is the required output, it is probably better to use a few subjects, and relate their electromyograms produced with particular foods to their complete mastication and swallowing.

Some hard and brittle foods emit sound during chewing (van der Bilt *et al*., 2011). These sounds can be directly detected during their transmission through the skull (Van Der Bilt *et al*., 2010). Chewing progress could be monitored, but again, different subjects broke down the food in distinctive patterns. However, different types of foods registered significant differences, independent of the subject, which were related to the mechanical properties of the foods measured on external instruments. In this example, however, measurements made directly on human subjects have a distinct advantage. The foods are subjected to dilution with saliva, so that the sound emission is related to the changes in mechanical properties not only via fracture but also via the plasticisation of the material by saliva. Interpretation of the sound records is complex, but there is some hope of extracting the effects of both breakdown and lubrication. This is not possible where sound emission is measured on intact samples on external acoustic devices (Chen *et al*., 2005).

Advances in magnetic resonance imaging now allow real time imaging of chewing and swallowing sequences. For dynamic studies, proton density images are recorded, but the technique can also detect changes in muscle work done, by examining static T2 images during the chewing sequence (Yamaguchi *et al*., 2011).

Even this method is uncomfortable for the subject, and by far the most illuminating tool is X-ray video imaging, where the food is labelled with heavy metals. The time course of chewing and swallowing is easily visualised, and shows the fragmentation of the food, the action of the tongue and the formation of boli which are swallowed as pulses of material. The X-ray dose is high, and these experiments can only be performed under clinical supervision, but are now widely used in observing disorders in both chewing and swallowing. An example can be viewed on YouTube: http://www.youtube.com/watch?v=umnnA50IDIY.

6.2.2.2 *Sampling the action of the machine*

As for other unit process studies, the operation of the machine can be deduced from observation of its effect on the materials it is processing. For foodstuffs and the mouth, this simply requires a human subject to chew under controlled conditions and expectorate a sample which can be measured at any appropriate structural level. More detailed microscopic examination will be reported later, but simple observation shows a common pattern for all food types. Examples for "naturally structured" food (meat) and a man-made structure (biscuit) both show breakdown over the first 10 to 15 chews (see Figs. 6.3 and 6.4). Thereafter, reassembly occurs, and the human subject swallows. This is in reasonable agreement with the edometer and myograph. Prolonged forced chewing results in a finely divided material, which the subject reports as difficult to reassemble and swallow.

Breakdown of foods by mechanisms other than fracture can also be observed by the same approach. The reduction in viscosity of sauces and soups thickened with starch can be measured once salivary amylase is introduced, and the collapse of ice cream and chocolate at mouth temperature is easily observed, either on expectorated samples or by *in vitro* experiments.

These are experiments that can be easily repeated by the reader at home, with any food type. As reported by Heath (1991), we have noted that individual patterns of chewing may be different between subjects, but the overall sequence is common.

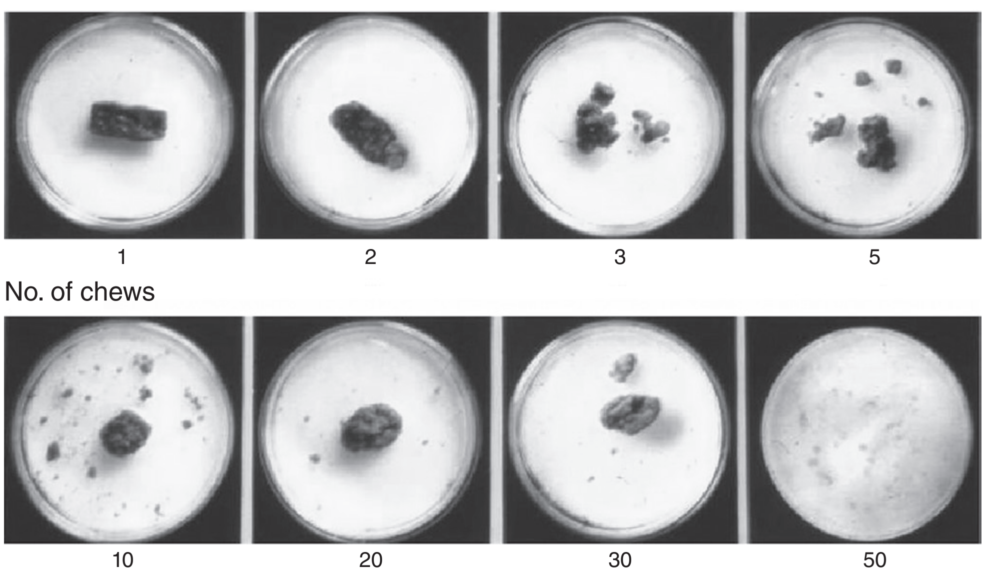

Fig. 6.3 Chewing process of cooked beef muscle. Reproduced with permission from Lillford (2000) The materials science of eating and food breakdown. *MRS Bulletin* 25(12), 38–43. Cambridge University Press.

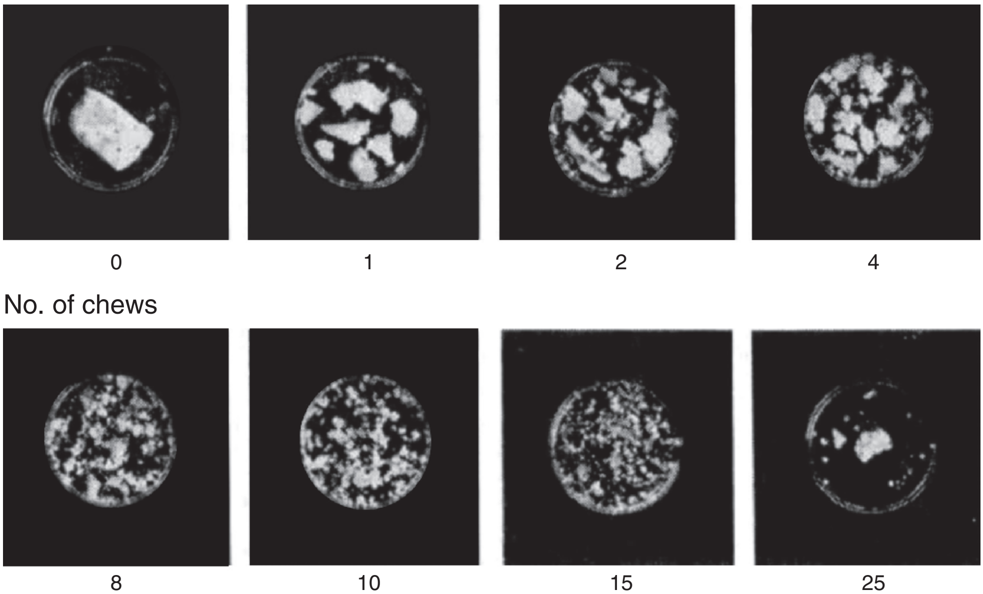

Fig. 6.4 Chewing process of a dry cracker biscuit. Reproduced with permission from Lillford (2000) The materials science of eating and food breakdown. *MRS Bulletin* 25(12), 38–43. Cambridge University Press.

6.2.2.3 *Direct interrogation of the response*

Sensory research with human subjects has the advantage that they can convert the sensations they experience into words. In daily life we do not apply a high level of analytical thought to eating and texture perception. Instead, we behave in a scripted fashion (Abelson, 1981), where visual recognition of a food type causes us to act as if we know what chewing procedure is required and what the expected stimuli and response should be. Only if some unexpected stimulus is encountered (such as stones inside fruits, or unexpectedly tough meat), do we register any judgement. However, provided training is performed on the use of individual descriptors, a group of average consumers can be transformed to a "panel" capable of scoring, reproducibly and with reasonable agreement, the sensations (otherwise known as attributes or descriptors) of any food type.

Szczesniak (1963) attempted to define a general set of verbal descriptors that clearly have their origin in the physical properties of food materials. These include terms describing the properties of the original material (such as soft, hard, tough, elastic, viscous); and geometric terms which clearly relate to the broken food (gritty, grainy, fibrous). Descriptors relating to reassembly of the swallowed bolus were not specifically identified. These initial terms are not those of physics and materials science, but subsequent training allowed subjects to score more recognisable parameters such as hardness, brittleness, elasticity, viscosity, particle size and shape. The correlation of these descriptors with the physical properties of the materials measured by a simple mechanical testing device, does not mean that we understand the actual fracture processes in the mouth, but the use of the mechanical "texturometer" (Szczesniak, 1963) still serves as a valuable quality control tool, particularly when a measurable difference between samples of a particular food type is required.

Later work with panels of subjects shows that the sequence of breakdown is easily identified and reported. When asked consciously to record their sensations occurring during chewing, a time sequence of stimulus and response is noted. Furthermore, panellists can agree on the quantitation of these descriptors for a particular type of food (Lillford, 2000). The emphasis has now moved from the search for a general set of descriptors, towards specific and detailed sets for each type of food. This is hardly surprising in view of what we now know about the use of the mouth and the specific "reprogramming" of its action with different food types. A remaining problem with the approach of verbal interrogation is that most panellists are unfamiliar with the terms of basic physics and engineering. For example, stress and strain are often regarded as synonymous, toughness may not be used within its strict physical definition, and "thick" (a distance) may be used to describe viscosity (a flow parameter). Panellists also produce descriptors, which have no direct physical analogue, such as "creamy". Whilst such terms are easily recognised in common usage, the physical stimuli giving rise to such a response require careful investigation. Therefore, scrutiny of the verbal output is necessary, and its relation to physical stimuli requires experimentation. Continuing attempts to achieve this are described later.

Nonetheless, the trained subject is very well able to articulate a whole host of descriptors relating to the mechanical response of food to its oral processing. Whilst interpretation may be complex, the information is the most relevant for food scientists.

6.2.3 Summary

The action of the mouth as a machine is exceptionally complex, but methods are available to study the forces, deformations and the complete course of chewing and swallowing in real time. Our knowledge of the mechanical operation of the machine is limited by the amount of studies performed rather than a lack of measurement methods. A major uncertainty remains, however, which relates to the chief lubricant, saliva. No realistic techniques are yet available to examine the time-dependent quantity, composition, physical properties and chemical reactivity of this material during chewing and swallowing.

6.3 FOOD BREAKDOWN AND REASSEMBLY: A MATERIALS SCIENCE APPROACH

Because mouth action is so complex and cannot yet be modelled or simulated, an alternative is to regard the process engine as a black box, and examine its action by the measuring its effects on the substrates, i.e. various food types. This approach is analogous to the study of any processing equipment, where samples are taken during its sequence of actions. The approach is particularly favoured by food scientists, who are more interested in understanding and designing food types, than in the action of the mouth itself. Even this is not straightforward, since foods are far from simple materials. All foods display a structural hierarchy at a range of length scales. They are complex composites. We can separate those whose structures are built biologically (meat, fish, fruit, vegetables), and are selected or manipulated to make them more edible, and those that are wholly fabricated structures (baked goods, confectionary, ice cream, chocolate, soups and sauces), created by processing to achieve edible properties. This section will examine what these various structures are, how they are broken and reassembled, and what we have learnt by the application of basic materials physics to these particular finished food structures.

6.3.1 Natural structures

6.3.1.1 *Muscle-based foods*

Meat

Striated muscle is a highly aligned fibre composite of contractile fibres and elastic connective tissue. Willems and Purslow (1997) studied the failure properties of beef muscles and showed that the properties of single fibres are very different from bundles; the former failing at low strain (2%), whereas the latter fail initially at 25% strain, but do not completely fracture until at least 75% strains are applied. This is due to the extensibility of the connective tissue sheaths surrounding bundles of fibres, and it is the mechanical properties of these higher-order structures which are presented to the mouth. They observed that cooking *increased* the stress and strain to break of fibre bundles. Whilst the stresses (12 kg/cm^2) are easily reached by the molars, the strains can reach 250%, which implies that cooking is counterproductive, if complete breakdown is to be achieved. However, examination of chewed meat shows that we need only to separate large fibre bundles by delaminating the connective tissue rather than by fracturing every bundle. Attachment of muscle bundles to each other via remnants of connective tissue does not necessarily prevent restructuring to a swallowable bolus and may even assist the collection of small fragments (see Fig. 6.3). This highlights the need to examine mouth action alongside the performance of accurate fracture mechanics on specially prepared material. Our studies of larger meat pieces, failing under tension and across the grain of fibres, showed failure at strains a low as 20% for cooked chicken and pork. Beef muscles could sustain strains of up to 100%, but only when cooked at conditions where gelatinisation of connective tissue was low (Lillford, 2001). Willems and Purslow (1997) also examined the effects of conditioning (i.e. hanging the muscle to allow resolution of rigor mortis) and cooking. Conditioning muscle allows catabolic enzymes to weaken all the structural components of the composite. This includes the connective tissue around fibres, the contractile proteins and the intracellular framework of titin and nebulin. After cooking, both the fracture stresses and strains were found to be reduced relative to unconditioned material, which demonstrates "tenderisation", but fracture strains remain high so that complete fracture of all bundles will rarely be achieved in the mouth.

The advantage of coarsely comminuted meat products (burgers) now appears clear. A machine rather than the mouth is used to breakdown the high strains of raw meat, and the particle sizes produced are comparable to those identified in chewed boli. These particles are reassembled by salting and pressing, which glues the particles together with gels of actomyosin or other added polymers. Furthermore, if these particles are not heavily compacted, the resultant composite will have a much lower strain to break after cooking than the natural meat structure (Reig *et al*., 2008).

In principle, we now understand the relevant physics of meat breakdown in the mouth, and the influence of processing and raw material upon it. The reassembly process to form a bolus is less well understood. Obviously saliva will be entrained, but the preferred versions of these high-water-content foods are frequently described as "juicy". This implies that liquid is released spontaneously during chewing, and the structures are self lubricating, or at least do not require the active production of more saliva to form a swallowable bolus. After cooking, meat becomes a porous, liquid-filled structure, and NMR relaxometry is capable of giving an indication of the pore size distribution, and thereby the location of the liquid phase. It is encouraging to see that only the liquid in larger pores, capable of being expressed during chewing, correlates with sensory juiciness, whereas liquid retained in intact fibres is not detected (Reig *et al*., 2008). In fact, the intrafibre liquid appears to correlate negatively with the "resistance" to the first chew. This is also sensible, since the modulus of individual fibres should relate to their protein density, and therefore inversely to their liquid content. It is evident however, that not enough is known about

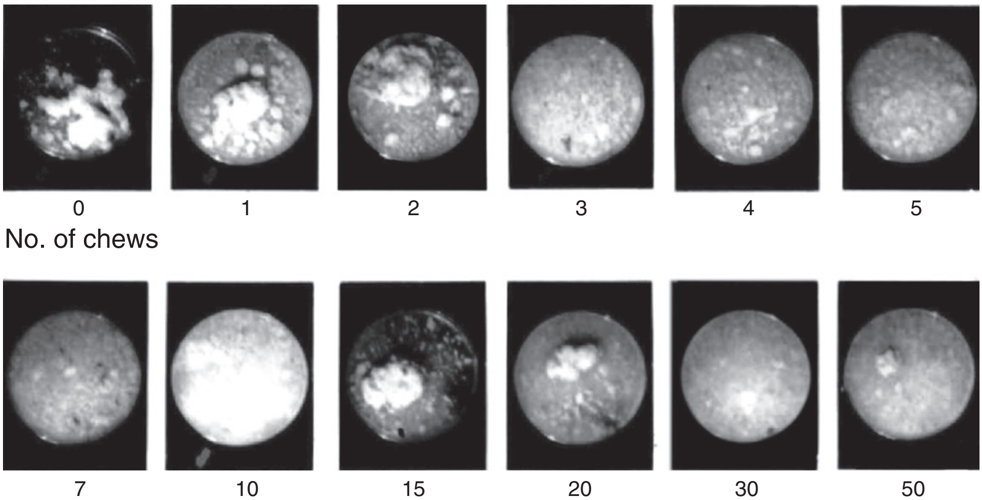

Fig. 6.5 Chewing process of cooked fish.

the structure and mechanics of forming boli to describe accurately the physics of the later stages of mastication. It is unreasonable to propose that a measurement made on the original, undisturbed structure can ever predict the properties of the total breakdown and reassembly process.

Fish

Whilst the organisation of the muscle tissue is similar to land-based animals at the level of the myofibril, the structural organisation at higher level is very different. Fish muscle is organised in myotomes, easily visible by eye as the flakes in salmon. The connective tissue of fish is also much more heat labile, forming soluble gelatins. Raw and cooked fish therefore have much lower breaking strains, and are easily broken in the mouth. In some cases, particularly after extensive cooking, a preponderance of individual small fibres is rapidly formed during chewing, making collection and clearance of boli more difficult (see Fig. 6.5).

Results of NMR relaxometry mentioned above also correlate with the "juiciness" of cooked fish (Lillford, unpublished results).

Other muscle tissue

Not all muscle is striated, so its fibres are not aligned over the distance of a mouthful. Heart muscle, squid and octopus mantle, mollusc tissue etc., have the same contractile system at the molecular level, and the same connective tissue components, but these are arranged less unidirectionally. The rubbery texture obtained after cooking is due to the conversion of the load-bearing connective tissue to a highly extensible matrix, with properties not unlike an entropic rubber (Vincent, 2008).

6.3.1.2 *Fruit and vegetables*

Biology and food science use the same terminology to describe this class of materials. They are cellular composites, but materials science also refers to these as fluid-filled foams, which allows the physics to be “borrowed” from other studies of more uniform man-made foams (Ashby and Gibson, 1983). In fresh material, the cell walls and membranes remain intact, and any remaining turgor pressure prestresses the cell wall. Over-ripe, post-harvest and cooked tissue have the same architecture. However, as membranes fail, turgor is lost and the cell walls (which are themselves a fibre composite of cellulose, hemicelluloses and pectins), change their mechanical properties. This has been reviewed previously by Vincent (2008). These changes are very relevant to the eating process. Breakdown and size reduction is necessary for swallowing, and this requires crack propagation through relatively brittle materials, but the crack pathway depends on the state of the tissue, and occurs either through cell walls or around them, depending on their post-harvest state, pretreatment and cell wall composition. Micrographs of the typical crack pathways produced by chewing are shown in Figs. 6.6 and 6.7.

The breeding of plant foods has (mostly unknowingly) produced vegetable tissue designed with particular fracture properties, suited to the human mouth action (Lillford, 2001).

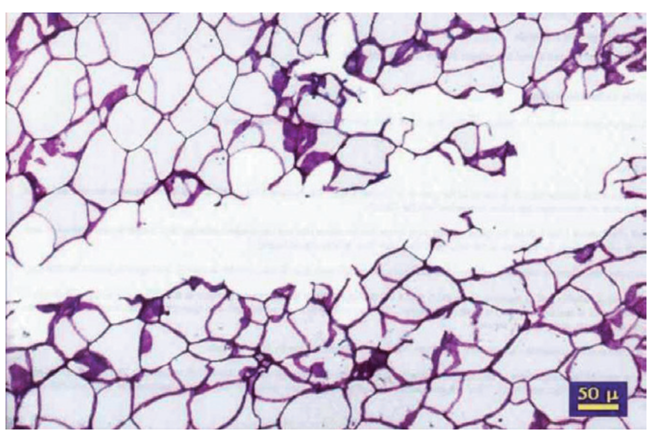

Fig. 6.6 Fracture through cell walls of fresh vegetable. Reproduced with permission from Lillford (2000) The materials science of eating and food breakdown. *MRS Bulletin* 25(12), 38–43. Cambridge University Press.

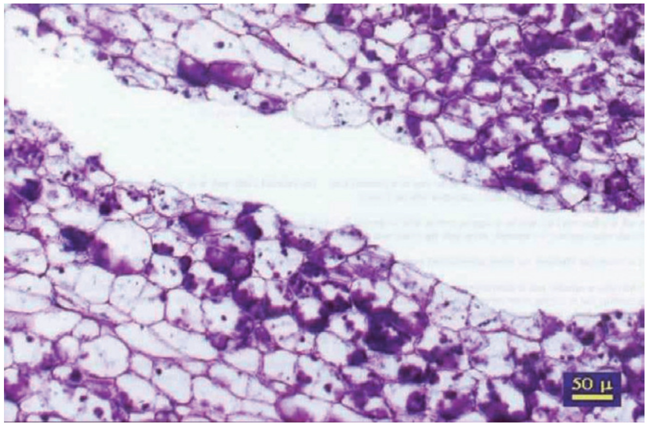

Fig. 6.7 Fracture around cell walls of cooked vegetable. Reproduced with permission from Lillford (2000) The materials science of eating and food breakdown. *MRS Bulletin* 25(12), 38–43. Cambridge University Press.

Summarising the varied but quite detailed knowledge of fracture and failure of edible vegetable tissue we know the following.

Fresh tissue
Turgor pressure on the cell walls of fresh tissue leads them to be brittle composites cracking at low strains under tension or compression. The cracks propagate through the stiff cell walls. The critical stress concentration is easily reached by the teeth, and its measured value seems to relate to perceived hardness. The speed of crack propagation is extremely fast and sound is emitted which is also associated with crispness. This has been extended further, to relate the ease of fracture to tooth geometry (Agrawal and Lucas, 2003).

Even when total turgor is lost, if the cell walls are still largely intact, they enclose an incompressible liquid which cannot escape rapidly during deformation (Warner and Edwards, 1988). Stresses are transmitted to the wall at a rate determined by chewing, which can still produce brittle fracture. The fracture rate, and therefore the sound emission, is chewing-rate dependent; an experiment which readers can perform themselves, simply by changing the rate of biting into raw carrots.

The use of water as a stress transmitter is also used in fruit analogues. Crosslinked hydrocolloid networks exhibit the same kind of fracture and failure mechanisms. Under compression, water cannot flow rapidly through the network so that high stress and high strain rates on the network are sufficient to fracture the structure. Somewhat like vegetable tissue, lubrication is produced at each fracture. This is the principle of reforming fruit, by reshaping fruit purees in a gelling matrix of hydrocolloid.

Cooked or over-ripe tissue

Thermal processing or the action of degredative enzymes hydrolyses the components of plant cell walls. The result is that cell walls develop plasticity as the cellulosic fibres delaminate from the pectic substances. Cracking is slowed, no sound is emitted and fracture occurs around cells rather than through their walls, retaining water in cellular spaces. When cells become excessively leaky, no stresses are transmitted by the retained liquid. The materials become softer, and in the limit may release all liquid under stress. They then collapse via buckling, behaving as a compressible foam, which is more difficult to break.

Storage tissue (nuts, seeds and root crops)

If the structures contain significant stored biopolymers, such as starch or oils, their mechanical properties will be different from tissues with a low viscosity cytosol.

For nuts and seeds, shells and hulls are usually removed prior to eating, and only the kernels are consumed. The kernels of nuts and oilseeds typically contain protein and oils in separated organelles, embedded in a carbohydrate framework, and at maturation contain low moisture content. As a result, they are brittle, and the work of fracture is low (Nikzadeh and Sedaghat, 2008). Fracture by crack propagation is a property related to not only to material and structure, but also to size, since greater volume allows the storage of more strain energy to propagate the advancing crack. Crushing between the teeth can provide sufficient strain energy except for the smallest of nuts and seeds. The load-bearing matrix is carbohydrate, and it is not surprising therefore that drying or roasting, which reduces moisture content, increases the fragility as the matrix moves towards a glassy state, whilst the fracture path around oil bodies remains unchanged. The initial fracture paths do not necessarily pass through the oil bodies, so the lubricating effects of oil are only achieved after extensive chewing.

Where protein and starch are stored, the effect of heating can be quite different. At low moisture contents, such as those found in peas and beans, starch cannot gelatinise, and dry heating (roasting) simply causes further drying to move both the matrix and the inclusions towards their glassy states. The material becomes almost homogeneous with respect to mechanical properties and cracking does not occur so readily at the interface between components. The materials become hard and unbreakable in the mouth, because the breaking stress is very high. Wet heating plasticises both the matrix and starch, allowing the latter to gelatinise. Provided water contents are sufficient to move the materials to their rubbery state, both fracture stress and strain are low enough to achieve fracture. No liquid release occurs, so that beans and mature peas are most often described as “dry” or mealy”.

In root crops, such as potatoes, the harvested state is at high moisture content. Eaten raw and at high turgor a potato is crisp, since fracture occurs rapidly and through the cell walls. During roasting or wet heating, the retained starch gels, providing a closer match between the cell wall properties and the contents. Fracture can occur either through the cell walls or around them, the latter giving rise to "mealy" textures. The differences appears to be related to cell wall properties and hence the variety of the crop. Since both components are viscoelastic, fracture will be slow and no sound emissions will occur. The achievement of crispness in cooked potatoes (fries and chips) is a property of selective dehydration and some steam-driven expansion, reducing density. This relates more to the mechanics of baked cereal products (see below).

Inedible vegetable tissue

There is a large volume of vegetable biomass that is not used for human food. This ranges from woody tissue of plant stems and trees, to highly oriented fibre composites, such as some leaves and most grasses. In the first case, cell walls are lignified, i.e. crosslinked by thermally stable polyphenolic bonds which simultaneously dehydrate the cell walls. The stresses and strains become beyond the capability of the human mouth to fracture. Even if the fracture is performed by machine, the resultant sawdust is unacceptably dry and requires delivery of large quantities of saliva to produce an acceptable bolus.

Woody tissue is an extreme case, but leaf tissue can range from the edible (lettuce) to the inedible (meadow grasses). The palatability of grasses is partly determined by the bitter secondary metabolites, but both these and their structural architecture can be manipulated by breeding. The difficulty of breakdown during chewing relates to the content of vascular tissue, and its alignment in the specimen (Toole *et al*., 2000). Fracture across the grain is prevented by the high stiffness and work of fracture, so even if fluid is released during chewing, fibres of the same length as those in the original structure remain, and bolus formation requires rolling up the long axis of the residual fibres. For grasses, with their high content of stiff aligned fibre, this is almost impossible in the mouth.

This also explains why most stem tissue of vegetables is prepared for eating by prechopping across the grain, producing shorter fibre lengths.

6.3.1.3 *Summary*

So far, we have considered foods whose structures are built naturally, by the growth of tissue designed for the purposes of the animal or plant. We have seen that work of fracture is critical to the breakdown in the mouth, and this property for natural composites is determined by the stress and strain to break. Mastication induces compressive and tensile deformation, but the strains available are relatively small. Aligned fibre composites, whether from animal or vegetable tissue, will be difficult to break if either the matrix or the fibrous elements require high strains at break, i.e. they are tough in the context of mouth action. Examples are: muscle tissue with extensive and thermally resistant connective tissue; muscle with strong fibres, even after the reduction of connective tissue adhesion (overcooked mutton and beef); chemically crosslinked (woody) plant tissue; highly reinforced vegetable fibre composites (grasses and some leaves).

Conversely, plant tissue predominantly consisting of water-filled cellular architecture breaks at relatively low strains and releases lubrication at each fracture (most fruits and some leaves). They appear ideally designed for eating. Indeed, in the case of most fruits this is the case, since seed dispersal is animal assisted. We have even learned to select for this property by eating some seeds at low maturation (petit pois), where cell contents consist of sugar rather than starch.

Where cellular tissue contains stored starches or oils, such as nuts and mature seeds, we chose to select for larger samples (peanuts), which when raw can be fractured with the energy stored during compression between the teeth. The effects of heating are crucially influenced by moisture content. For starch-containing structures, the plasticising action of water is important to reduce the failure parameters to those achievable by the teeth. Dry heat can increase the work of fracture to levels greater than the mouth can achieve.

Whilst we can crush the smaller seeds of cereals between the molars, the initial seed is hard and the resultant comminute is dry and "floury". Much better to rely on the baker's art to manufacture novel structures which are more pleasant to consume.

We will now consider foods which are fabricated by processing. All of these have been developed empirically, but are accepted *because* they can be broken and lubricated in the mouth. The following discussion will attempt to diagnose what structural principles have been deployed to achieve these products.

6.3.2 Baked goods

The major components of graminaceous seeds are protein, starch and other cell-wall carbohydrates, providing a calorie-dense raw material. The advantage to human sustenance is that these seeds can be stored dry and transported relatively easily, thereby allowing survival through winters, and releasing a population from hunter/gatherer tribes to farming and centralised civilisation. However, the conversion of seeds to an edible food requires processing. The craft skills of the baker have developed in every civilisation, to form bread, cakes, biscuits, pastry, tortillas, pizza, noodles etc. Note that all of these structures can be eaten. Empirical baking processes that produce inedible structures have not survived.

The type of product depends on the properties of the raw material. The peculiar properties of wheat proteins allow the foam structure of bread to be formed, whereas maize is more often converted to thin sheets, or crunchy biscuits. The types of products are too numerous to be reported individually, but most products contain a high phase volume of air: they are foams. At high water activity A_w, the structures are soft, (e.g. leavened and flat breads; cakes). At lower A_w, the structures become brittle and crisp (biscuits, extruded snacks). The processes of dough formation, fermentation, proofing, baking, extrusion etc. are reviewed elsewhere (Dobrasczczyk, 2008). We focus here on the chewing of finished products.

6.3.2.1 *Breakdown of foams*

The mechanical properties of air-filled foams have been reviewed by Ashby and Gibson (1983). By treating the open cellular structure as a series of interconnecting beams, the modulus and fracture properties can be calculated in terms of the density of the foam, and the dimensions and properties of the beams or cell walls. Using this formalism, Attenburrow *et al*. (1989) showed that the critical crushing stress for a model baked product was related to the bulk density. Also, this critical stress correlated with perceived "hardness". However, the values are significantly influenced by water content, and the fracture stress–strain curves change in their form. At $A_w < 0.33$, the foam cells fracture individually until the whole specimen breaks. At higher moisture contents, the specimens deform plastically, and fail at much higher strains. Control of moisture in the cellular finished product determines whether the materials are soft (bread) or brittle (extruded snacks), and their consequent fracture and failure has been studied and reviewed by Corriadini and Peleg (2008).

Soft foams

Bread and cakes are soft composites, and their modulus and critical failure stress can be related to overall bulk density, as predicted. So the dominant factor in bread hardness will be the foam volume. However, for bread, the stress–strain curve under compression changes with the number of applied cycles. In the first, a shoulder appears, which is not visible in subsequent cycles. This was related to bursting of remaining closed cells in the bread. In principle, this change may be detected during chewing, but has not been reported.

The phenomenon of staling is well known and its effects are detectible in the mouth, primarily as a significant increase in "hardness". Since bulk density does not change significantly in the time taken to stale, the effects are assigned to water loss and migration (Chinachoti and Vodovotz, 2000). A degree of hardening would be predicted as water is lost, simply from the increase in modulus of wall material, but this is not sufficient to explain the effect. In bread the polymers are above their glass transition, but low-molecular-weight fractions of amylase and amylopectin can recrystallise ("retrogredation"). The molecular details of retrogredation are still not understood, but recrystallisation will increase both modulus and critical stress levels in any foam, thereby increasing the forces necessary to compress and fracture bread between the teeth.

Brittle composites

Corriadini and Peleg (2008) have shown that force–displacement curves for these materials are jagged, as individual cells break, and are also irreproducible between samples of the same material. However, the mechanical signature of different materials can be described using the smooth skeleton of the curve and its superimposed jaggedness. Probably, both will be detected during chewing, but the dominant response is to the fast brittle fracture and sound emission, which is reported as crispness and crunchiness. These properties are associated with the glassy state of the load-bearing members of the cell walls. Therefore, it is not surprising that exposure to water, in the form of vapour during storage or saliva during chewing, will plasticise the system. Soggy and soft textures are the predictable result. However, the exact moisture levels at which this will occur is less predictable, since biopolymers have broad glass transitions, and the cell walls are themselves composites of starch, protein and sugar, depending on which particular baked product is considered. This remains an active area of experimental research.

Lubrication

Baked products absorb saliva and the descriptors of "dry" and "moist" are used by consumers. This can be related to the physics of moisture uptake into porous sponges. The rate of liquid uptake into a porous material is given by the Washburn equation:

$$t = \frac{K\mu}{pg}\left[h + h_e \ln\left(1 - \frac{h}{h_e}\right)\right] \tag{6.1}$$

where K describes the geometry and the packing of a given powder bed;

μ is the liquid viscosity;
p is the liquid density;
h_e is the height rise at infinite time, and depends upon the surface tension of the liquid; and the contact angle between particles and liquid.

Though no dynamic experiments have been reported for in-mouth studies, we can postulate the following mechanisms from the physics of the materials. If the pores are small and the surfaces are hydrophilic, saliva will be actively sucked into the structure. When saliva is rapidly absorbed, structures become soft and crispness is lost, as cell walls are plasticised. However, if the material is of very low density, cell walls are thin and buckle easily when their modulus is reduced. Mechanical collapse can occur even under gravity or the slightest pressure by the tongue. This is usually described by the physically incorrect term of "melting" in the mouth. We also know that amylase in saliva will digest gelatinised starches. If this material is part of the load-bearing structure, then chemical action will speed the entire process.

It is common knowledge that collapse caused by water plasticisation can be slowed or prevented if the structure is completely covered by fats or oils (e.g. fried bread, croutons). Then liquid uptake is very slow, brittle structures survive and crispness is retained.

The sensory impression of "moistness" in cakes was briefly examined in the Unilever laboratory (author's unpublished results). As expected from the arguments above, moistness increased with fat content, which was presumed to be associated with reduced capillary suction by changing the contact angle at the capillary wall, and the slowing of water mass transfer into the cellular matrix. Moistness appears to be associated with the reduced saliva requirement prior to swallowing, rather than the delivery of any lubricant from the structure itself. Attempts to rank moistness by measuring water content or physical properties of boli failed. In fact, subjects chewing and swallowing the same range of cakes produced entirely different boli in different sessions. In particular, boli were looser and wetter on cold days compared with those prepared on warmer days. The limits of structural states which normal subjects can swallow are still not characterised. They are probably related to the cohesion and surface properties of the boli formed, but should be expected to vary with the individual.

6.3.3 Dairy products

There is only so much milk we can drink, so its obvious nutritional value can be preserved and converted to a more solid state by fermentation and processing, to produce yogurts and cheeses, for example. The literature on the physics, chemistry and biology of the dairy product industry is immense, but focuses on coping with the variations in milk to produce edible structures developed empirically over many generations (Fuquay *et al*., 2011). Fewer studies on the eating processes have been reported. However, we can deduce the probable oral processes, by consideration of the material properties of these structures, together with the available reports of masticatory processing. There is such a range of product types that the comments here will necessarily be brief.

6.3.3.1 *Yogurt*

This has been used as a model food for swallowing. The structure requires no mechanical breakdown, and is easily swallowed. The work of Shama and Sherman (1973) suggests that its properties are sensed, not simply by its flow rate, but may also be related to the shear stresses necessary to position it for swallowing.

6.3.3.2 *Cheeses*

These can range from soft, elastic to hard, brittle solids, but all can be described as gelled, water-continuous protein networks, containing various amounts of oils and fats which act as a soft filler. Luyten and van Vliet (1996) have studied the change in fracture mechanisms for maturing cheeses. Under compression, fracture stress halves with maturation time, but breaking strains decline from 150 to 20%. Thus the work to fracture declines by at least a factor of 10, which explains the reported textural changes from “rubbery” to “crumbly” as cheeses mature.

6.3.3.3 *Cream*

Creams are water-continuous emulsions, stabilised by the milk-fat globule membrane and the high concentration of soluble protein and micellar casein. Whipping entrains air bubbles, stabilised by fat globules at the interface. Their structures are weak, requiring no comminution, and the combination of warming and the action of salivary enzymes and mucin cause the structures to weaken rapidly in the mouth. Expectorated samples immediately prior to swallowing show that the emulsion is largely intact, small air cells in whipped cream remain, so that the material is easily manipulated and swallowed. Interestingly, this type of product is almost universally liked, so that "creaminess" is a preferred characteristic of many foods in their late breakdown phase. This probably relates to the easy manipulation and swallowing of the bolus.

6.3.3.4 *Ice cream*

High-fat versions of ice cream are simply frozen whipped cream. Ice crystals melt rapidly in the mouth, but if large will be detected by the tongue and soft palate during movement by the tongue, and the product will be reported as "icy", rather than "smooth". Expectorated samples show a similar emulsion structure to the equivalent cream. Lower-fat versions contain thickeners, stabilising the initial structure, and attempt to match similar in-mouth rheology to their high-fat version after melting.

6.3.3.5 *Butter*

Churning of cream produces a fat-continuous product, structured by crystal networks, but still containing some of the globules of fat present in the original cream. These globules are stabilised by the unique fat globule membrane formed originally in the milk. The stabilising crystal network partially melts at mouth temperature, and after mixing with saliva, expectorated samples show inversion of the emulsion structure to that reminiscent of the original cream. This behaviour is a fundamental property of butter, and all successful substitute margarine and lower fat spreads must also show this in mouth inversion. If the crystal matrix does not melt in the mouth, the products are described as "waxy" or "greasy". Therefore, the mouth appears to detect differences between fat- and water-continuous soft solids, but the process by which this is done remains uncertain. It is possible that this relates to rheological or frictional properties of the materials which are not yet fully understood. Once again this demonstrates the sophistication of sensing and feedback in the oral cavity.

6.3.4 Confectionary

The artisanal skills of generations have produced an enormous range of structures. This class of foodstuffs are generally regarded as treats, probably because of their sweet taste, but perhaps also because of their interaction with the oral cavity. Many of them have the characteristic of being reduced to a swallowable state by processes other than chewing (i.e. their structures either dissolve or melt in the mouth).

6.3.4.1 *Sugar glasses*

Boiled sweets fall into this category. They are solids which, when first placed in the mouth, present a structure so hard that the forces required to break them are comparable with the strength of teeth themselves, despite the fact that glasses are mechanically brittle. Only if cracks are already present can they be broken at all. Our usual response is to size reduce the sample, by allowing the specimen to dissolve in saliva. Then the forces and deformation, due to crushing and bending between molars, are sufficient to produce stored energy capable of inducing cracks. Rapid fracture releases energy comparable to other brittle materials, and a crunching sound is emitted. The bolus forms as a suspension of small particles in a viscous liquid.

However, the confectioner uses the same physical principles of structure modification as the baker. The introduction of soft filler (air) reduces the mechanical strength of the glasses; a cellular architecture is produced, the thin cell walls are more easily fractured and a "crunchy" initial product results. Saliva readily dissolves the smaller fragments to give a viscous liquid which is easily swallowed. This design principle has given rise to crunchy sweets and even candy floss.

6.3.4.2 *Gelled structures*

Originally, these products probably developed around the peculiar properties of gelatin. This hydrocolloid can immobilise large amounts of water, producing a rubbery gel which at high dilution (table jelly) exhibits brittle fracture at strains achievable in the mouth by either tension or compression. In solid pastilles (low water content) these breaking strains are not easily reached in the mouth, but gelatin dissolves at physiological temperatures. Warming dissolves the structure to a viscous liquid, and the local strains on smaller samples allow size reduction. Other hydrocolloids, such as carrageenans and modified starches, can also form melting and dissolving structures, and can substitute for gelatin.

6.3.4.3 *Fat crystal networks*

Probably the world's most popular confectionary is chocolate. Structures range from brittle solids at room temperature to viscous liquids at physiological temperatures, all due to the unique melting range of cocoa fats. The processing of chocolate is carefully manipulated using temperature and mechanical working to produce fat crystal networks that can be shaped by casting and extrusion (Fryer and Pinschower, 2000). Its success as a confectionary depends on its flavour, and the taste impact of components present in cocoa and the added ingredients, such as sugar. But its “mouthfeel” is unique and depends upon its mechanical performance in the mouth. Recent studies of the eating process using different chocolate types and characterised groups of consumers, reveal fascinating results (Carvalho-da -Silva *et al*., 2011). Firstly, using electromyography and electroglottography (swallowing frequency measurement), three types of masticatory patterns were identified: “fast chewers”, “thorough chewers” and “suckers”. Individuals retained these chewing habits with different types of chocolate.

Expectorated samples of different chocolate preparations all show the production of a water-continuous emulsion of chocolate fat in saliva prior to swallowing, similar to the inversion process observed with butter. The fat-droplet particle size range is large, from below 1 to above a few hundred microns, and centred at around 20 microns. The swallowed state is therefore similar to that of a cream. The mouth-coating effect was measured and, for different chocolate types, influenced the in-mouth residence time. The effect of mastication on saliva production was also measured. Flow rates increased after consumption, but the protein content decreased. This was independent of the chocolate type, and may imply that the water-phase volume in the mouth induced during chewing is as important as the emulsifying action of mucin proteins.

6.4 CONCLUSIONS

There is now a developing database relating to the mechanical properties of biological materials that we call food. All are composite structures, some created by largely natural processes and others by the empirical skill of butchers, bakers, dairymen and confectioners. It would appear that success is achieved when these foods are structured so that they can be broken down by the available machinery of the mouth. Studies of the machine itself shows that variables it has at its disposal are:

1. Mechanical forces, strains, and the time derivatives of both, the ranges of which have been measured;
2. Temperature, with an upper limit of around 37 °C;
3. Plasticisation and solubilisation by water in saliva;
4. Emulsification, by active agents in saliva;
5. Chemical degradation, by secreted enzymes.

Examples of foods are identifiable that use any one, or any combination of these variables during their masticatory breakdown. This qualitative knowledge allows "design rules" to be proposed which explain why existing products can be less than optimal, can provide routes to the generation of new ones, and explain the role of ingredients in both. *But only if the architecture of the composite structures are known*. Where this structural information is available, we can go further, and specify the required physical properties of food structures and their components, at least for the initial stage of mastication.

Our knowledge of the late breakdown, reassembly and swallowing of these materials is much weaker. However, when the disciplines and techniques of dentistry and oral physiology are properly combined with physics, engineering and materials science, then great strides in understanding are achieved. The continuation of such multidisciplinary studies can only be of benefit to all concerned.

Finally, it would appear that our enjoyment of a food type and our rate of eating is linked to the ease of oral processing. The food industry has always attempted to produce food that is pleasurable to consume. It has largely succeeded in doing so, at large scale, with enormous variety and at relatively low cost. It will now need to exploit the "design rules" to provide the same pleasure, but from scarcer raw materials and at lower calorific value, if we are to cope with a growing population, and an obesity epidemic.

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