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Mastication and Swallowing: 1. Functions, Performance and Mechanisms

Abstract: The process of mastication involves movements of the tongue, lips and cheeks as well as the more obvious actions of the teeth and jaws. In recent years there have been significant advances in our knowledge of the relationships between these movements in human beings and of how the processes of mastication are related to the associated events of swallowing. In this, the first of two papers, we review the role of mastication in food processing and nutrition and the effect of tooth loss on masticatory performance. The paper also reviews new information on masticatory and swallowing functions in human beings eating naturally. The review relates this knowledge to clinical dentistry, notably to the relevance of a good dentition to the digestive process and practical considerations in the replacement of missing teeth.

Clinical Relevance: Dentists should understand the process of mastication because an adequate dentition can facilitate the general health and well-being of their patients. This understanding can also inform the clinical management of patients with a depleted dentition or otherwise impaired masticatory system.

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The functions of mastication

Mastication serves several functions. Its primary role is in the mechanical breakdown of solid foods; this prepares the food for swallowing and constitutes the first stage of digestion. Mastication stimulates the secretion of saliva,[1] which assists in the digestive process through its constituent enzymes[2] and facilitates swallowing by helping to lubricate and bind particles of food.[3,4] Chewing, by releasing chemicals from food, also contributes to taste and smell, which in turn contribute to the enjoyment of feeding and play a role in the cephalic phase of gastro-intestinal function. Finally, mastication has a positive influence on the development and maintenance of the jaw bones[5] and on the properties of the jaw muscles.[6] In this review, we will focus on recent work on the process of mastication and the subsequent transport of food to the stomach in human beings.

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Is mastication necessary?

Chewing breaks ingested food morsels into small pieces that can be swallowed easily. This process facilitates digestion by increasing the surface area exposed to digestive enzymes. However, it is not certain whether, or how much, a deterioration in masticatory performance, eg due to tooth loss,[7] can be detrimental to the digestive process. Farrell[8] investigated the role of chewing in food digestion. Volunteers swallowed weighed samples of chewed and unchewed foods, which had been sewn into small cotton mesh bags. The remnants were collected after transit through the gut and weighed to determine how much material had been removed. Farrell assumed that the absence of food residues indicated that the food had been absorbed, although this was not verified. On the basis of these studies, it was concluded that chewing is useful for intestinal absorption of some, but not all, foods and that three types of foods could be identified in this regard (Table 1). Support for this conclusion comes from the observation that glucose absorption and peak blood glucose levels are greater when various carbohydrate-containing foods (potato, apple, sweetcorn, rice) have been chewed before swallowing compared with when similar amounts of these foods are swallowed without chewing.[9] Furthermore, the fact that at least one of the substances (rice) is absorbed totally,

No residues whether chewed or not	Some residue if unchewed; no residue if chewed	Substantial residues if unchewed; some residue if chewed
Beef fat, fish, hard-boiled egg, boiled rice, bread, cheese	Roast chicken, stewed lamb	Beef, mutton, pork, liver, bacon, peas, carrots, potatoes

Table 1. Fate of different types of food in the gut related to whether or not they are chewed (Farrell[8]).

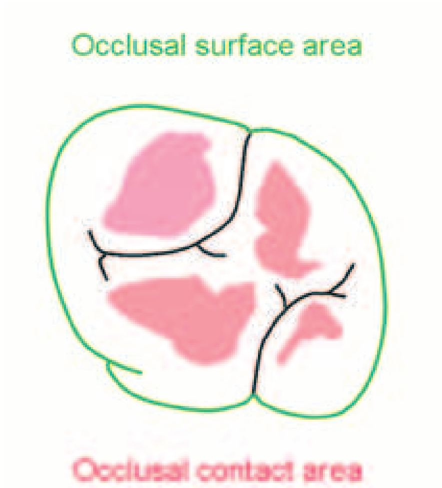

Figure 1. Diagram of the occlusal surface of a tooth showing the functional occlusal contact area (red shading). Note that this is usually smaller than the total occlusal area (green outline), unless there is a lot of toothwear.

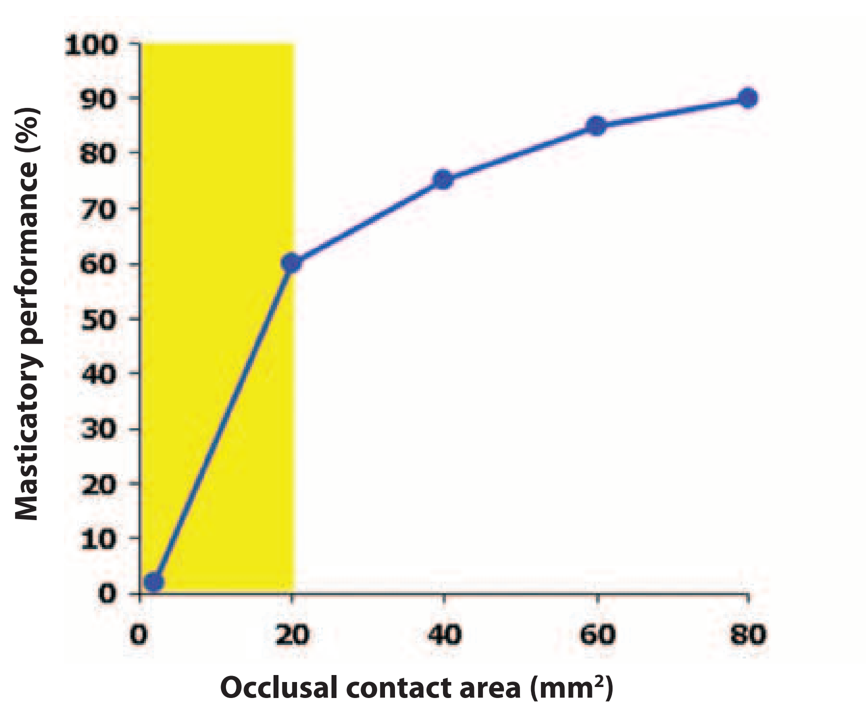

Figure 2. Non-linear relationship between masticatory performance and occlusal contact area (after Yurkstas[7]). In that study, masticatory performance was assessed as the proportion of the test food sample that passed through a particular mesh sieve. Note that the masticatory performance decreases markedly once the occlusal contact area is <20 mm^2 (yellow-shaded region). This relationship is part of the rationale for the shortened dental arch (see text).

regardless of whether it is chewed,[8] but increases blood glucose more rapidly after chewing, suggests that chewing can aid the absorption of even easily absorbed substances. From first principles, the increased rate of absorption following chewing could be due to the increased surface area of the chewed food and/or the rate at which the food reaches the small intestine, where almost all absorption occurs. In practice, however, the latter mechanism seems far less important. Indeed, there is evidence that prior chewing does not accelerate the rate of passage of radioactively-labelled meat through the stomach.[10]

The question of whether masticatory performance can affect gastro-intestinal, and indeed general, health will be dealt with in detail later.

Finally, there is the question of the importance or otherwise of the salivary enzymes, which are secreted partly as a result of mastication and are incorporated into the food by mastication. Perceived wisdom has generally been that the principal enzyme, amylase, plays little role in digestion as it is inactivated by the acidic conditions it encounters in the stomach after swallowing. However, some doubts have been expressed about this. It seems that with some – particularly dry brittle – foods, such as bread, up to 50% of the starch undergoes some chemical digestion within the mouth.[11]

Masticatory performance

Masticatory performance is usually assessed by the ability to break down food morsels into small particles, or as the number of chewing strokes required to prepare a mouthful of food for swallowing.[12,13] The efficiency of the process is extremely variable. Masticatory performance has been correlated with the number of occluding teeth in the mouth and, in particular, with the total occlusal contact area.[7] The occlusal contact area is the area of functional contact between opposing teeth. This depends on the amount of toothwear and can be considerably less than the overall occlusal surface area[7] (Figure 1). The relationship between occlusal contact area and masticatory performance is not linear (Figure 2). Masticatory performance deteriorates markedly with a less than about 20 mm^2 total occlusal contact area.[7]

Stage I transport
This the process by which ingested material is moved from the front of the mouth towards the posterior (premolar and molar) teeth.
Mechanical reduction ('true' mastication or chewing)
Solid food items generally cannot be swallowed directly. They have to be reduced in size to more manageable particles and brought to a 'swallowable' consistency.[3] This process of mechanical reduction includes the act of mastication or chewing, but often involves more than mere pulverization with the teeth.
Stage II transport
This is the transport of mechanically reduced solid food from the mouth proper towards the oropharynx. It is accomplished by a 'squeeze-back' mechanism (see text and Figure 7).
Swallowing
This is the process by which material accumulated in the mouth or oropharynx is transported through the hypopharynx (laryngopharynx) and oesophagus to the stomach. The swallowing mechanisms are somewhat different for liquids and solids.

Table 2. The stages in the feeding process.

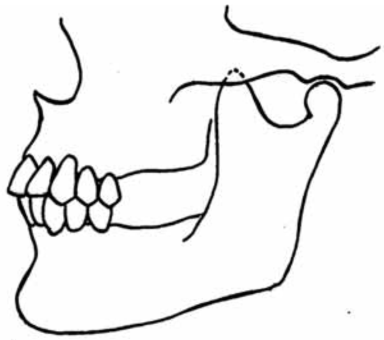

Figure 3. The shortened dental arch (Kayser[20]) In this example, the available chewing surfaces are those only on the premolars. Published with permission from Wiley-Blackwell Publishers, *J Oral Rehab*,[20] copyright 1981.

It is difficult to convert such figures into numbers of teeth because the functional occlusal contact area varies widely, even between teeth of the same type.[7] Also, the occlusal contact area alone does not account for all the variations in masticatory performance.[14,15] A study of 631 dentate people aged 37–80 years concluded that the main factors which correlate with masticatory performance are the numbers of functioning tooth units (pairs of occluding teeth) and the maximum molar biting force.[16] Factors such as age and sex were reported to have little effect on masticatory performance.[16] People with a reduced masticatory performance may compensate partly by chewing each mouthful for longer, although they still tend to swallow larger food particles than people with a good masticatory performance.[7,15]

Masticatory forces

The forces that can be generated between the teeth are affected by many factors.[12] Maximum biting forces in dentate subjects are in the range 500–700 N between molars and around 100 N between incisors.[17] Maximum biting forces in patients with mucosally-borne complete dentures are considerably less – approximately 15–30% of those developed by dentate people.[17] The forces generated during natural chewing are smaller, in the range of 70–150 N.[18] While such forces are well within the capabilities of dentate people (being only a fraction of their maximum biting capabilities), they may not be achievable by some wearers of mucosally-borne complete dentures. There is some evidence that both maximum biting forces and masticatory performance increase when complete dentures are supported by endosseous implants.[19]

The shortened dental arch and mastication

Patients tend to complain of reduced chewing ability when they possess fewer than 2–3 pairs of occluding posterior teeth.[20] Kayser[20] came to the conclusion that, on average, 20 functional teeth (6 pairs of anterior teeth and 4 pairs of premolars) are the minimum for acceptable masticatory function and aesthetics in the ageing patient. Indeed, such a reduced dentition – known as the shortened dental arch (SDA)[20] (Figure 3) – represents a compromise between what some dentists consider necessary for acceptable appearance and adequate for masticatory function and what can be easily maintained in a healthy state. In terms of masticatory function, there is evidence that people with 21 or more natural teeth tend to consume more nutrients, especially dietary fibre, than those with fewer teeth.[21] A recent review[22] lends support to the view that a shortened dental arch, comprising 9–10 pairs of occluding teeth, provides adequate oral function for most elderly patients. It should be noted that, although some dentists may favour the SDA concept, a recent study[23] found that patients rate it as the least favourable option for replacing missing molar teeth, when given choices of:

- No treatment (SDA);
- Removable partial dentures;
- Implants; or
- Cantilever bridges.

Consequences of impaired mastication

Since masticatory performance deteriorates with tooth loss, there has been considerable interest in whether this may also be associated with nutritional deficiencies and/or gastrointestinal disorders. It has been reported that individuals with poor dentitions and/or impaired masticatory function are more likely to have nutritional deficiencies,[24,25] or at least consume less than the recommended daily allowance of some vitamins and minerals.[26] Such individuals are also more likely to take medication for gastrointestinal disorders (eg antacids, laxatives[25]). These findings could be due to such individuals avoiding foods that are difficult to eat[13] and, indeed, there is evidence that individuals with reduced masticatory performance have lower than dietetically desirable intakes of high-fibre foods like fruit and vegetables.[25] However, such correlations are not necessarily indicative of simple cause-and-effect relationships. Although it is possible that a poor dentition leads to poor mastication and/or the avoidance of tough foods, and that this might lead to nutritional or gastrointestinal disorders, another possibility is that a poor dentition may be due to a lifetime of consuming 'unhealthy' foods which simply continues

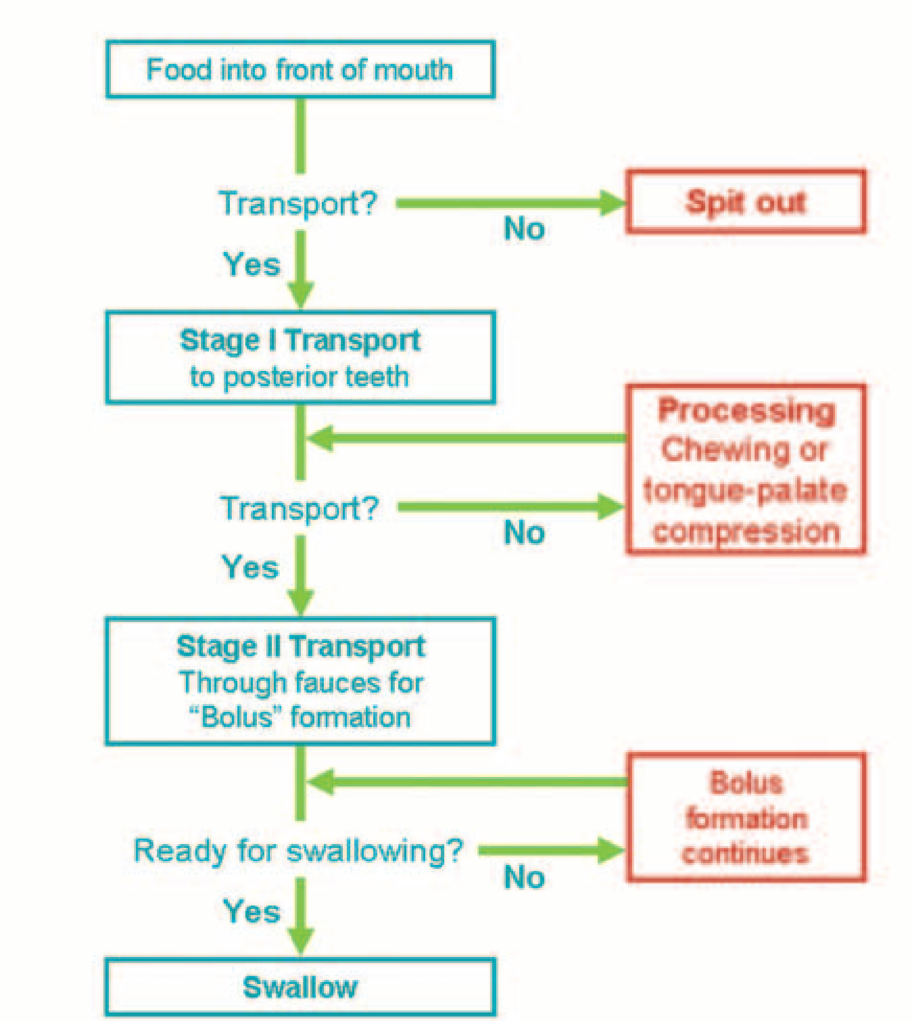

Figure 4. The stages in the feeding sequence. (see text) (cf Hiiemae[29] and Thexton[38]). Adapted with permission from Macmillan Publishers Ltd, *Br Dent J*,[29] copyright 2004.

after teeth are lost. Indeed, the relationship between nutrition and the state of a person's dentition is complicated, and many other factors that can affect diet include age, disability and socio-economic status. As the average age of the western population increases, there is growing interest in how dental status may affect nutrition in older people. One survey[21] found that, amongst people aged 65 and over, living independently at home, dentate individuals generally had a higher intake of nutrients (dietary fibre, protein, calcium, iron, niacin, vitamin C) than edentulous individuals. Again, depending on how one interprets the likely cause-and-effect, this finding might suggest that retention of a functioning natural dentition would help to improve the general health of elderly people. On the other hand, it has been reported that the provision of improved dental prostheses does not substantially improve nutrient intake in normal[27] or diabetic[28] edentulous patients.

One further consideration is that, if a poor dentition and/or masticatory function does indeed lead to the consumption of softer foods, these may contain more fat, which could increase the risk of cardiovascular disease.[13]

The feeding process

Feeding is essentially the process of ingesting and transporting food along the alimentary tract. For some (solid) foods, the transportation is interrupted by periods of mechanical reduction and mixing; the most obvious of these is chewing or mastication. Traditional accounts of mastication tended to concentrate on the food breakdown aspects. Indeed, anatomy texts still refer to the four 'muscles of mastication', even though many other muscles are equally, if not more, important in the overall mastication process. Observations in different species, including human beings, indicate that the oral stages of feeding involve a number of distinct and separate events, or processes. The nomenclature used to describe the various events originated from studies on sub-primate animals, but it is now clear that these descriptions can be applied to feeding in human beings.[29] These terms may not be familiar to all readers, and they are summarized in Table 2 and described in Figure 4. These events are sometimes embraced by the overall term 'mastication', but given the distinct nature of the transport processes, the term 'mastication' should be confined to the process of mechanical reduction of food particles.

Stage I transport

A food morsel is brought to the mouth by the hands. It may be placed into the mouth or bitten off with the anterior teeth. The lips confine the morsel and prevent leakage – this is sometimes referred to as creating an Anterior Oral Seal. The material is gathered on the tip of the tongue, which then retracts, transporting the food to the posterior teeth (molars and premolars). This is known as Stage I transport and involves a 'pull-back' process, which takes about one second, and is associated with retraction of the hyoid bone and narrowing of the oropharynx.[30,31]

Mechanical reduction (mastication or chewing)

Chewing cycles

Food is processed during repeated jaw cycling movements. Mostly these cycles are true masticatory cycles in which food is broken down by the teeth, but some soft foods are reduced predominantly, or only, by squashing them between the tongue and hard palate. Cycles in which solid food is reduced have three main phases:[32]

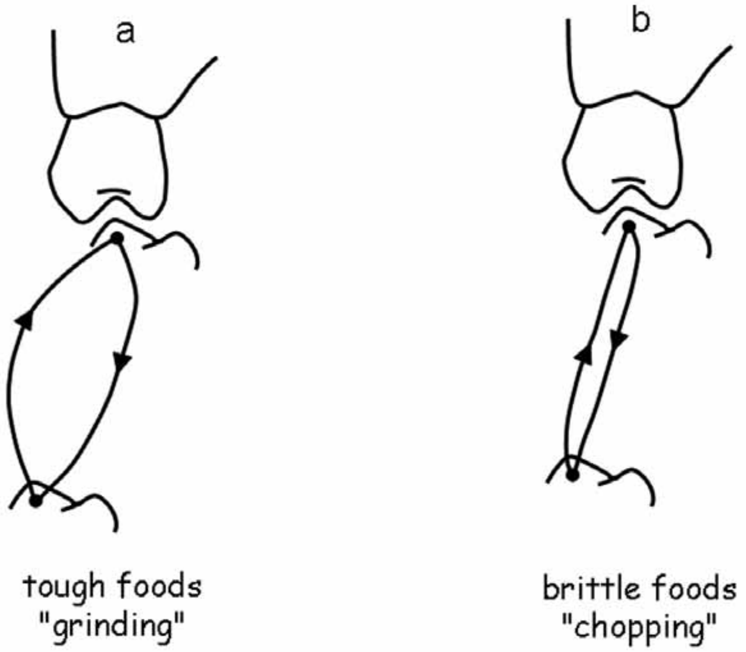

Figure 5. Diagrammatic representation of jaw movement cycles for different foods. There is a greater lateral component when chewing 'tough' **(a)** as opposed to 'brittle' **(b)** foods.

- An opening phase, in which the mandible is depressed and the upper and lower teeth are separated;
- A closing phase, in which the mandible is raised towards the maxilla and tooth-food-tooth contact occurs; this phase is sometimes divided into two (see below).
- An occlusal or intercuspal phase in which the jaw shows no discernible vertical movement, but bucco-lingual movements occur with teeth close together or in contact.

During all of these phases, the lips remain together as an anterior oral seal. These phases describe movements between the jaws in the vertical plane but, in addition, there are antero-posterior and medio-lateral movements (Figure 5).

The latter part of the closing phase together merging into the intercuspal phase has also been described as a power stroke, during which the food is compressed between the teeth.[29] This is similar if perhaps not identical to the description of phases in non-human species; in that case, the closing phase is sometimes subdivided on the basis of variations in the velocity of jaw movements into an initial fast closing phase, when the jaw movement is little impeded by the presence of food, and a later slow closing phase, when the jaw movement is slowed by the resistance of the food. It is evident that, in human beings, the pattern of chewing cycles varies with food consistency[30,33] and many individual variations have been described[34] (Figure 5). The transverse occlusal forces and lateral jaw movements associated with 'tough' and fibrous foods are a potential cause of denture instability. Indeed, it has been found that patients with conventional mucosally-borne dentures tend to have smaller lateral excursions during chewing than individuals with implant-supported dentures.[35]

Tongue movements

The actions of the jaws and teeth in food breakdown are accompanied by movements of the tongue and other soft tissue movements, which help to control the bolus.[31] Towards the end of Stage 1 transport, the tongue positions the food bolus on to the working side of the jaw using pushing and twisting movements. During the subsequent food reduction (chewing), the bolus is kept on the working occlusal surfaces by a combination of rhythmic tongue-pushing (moving the bolus buccally) and cheek-pushing (moving the bolus lingually). Other patterns of bolus control include transfer to the opposite side for further processing and aggregation of masticated food on the tongue dorsum prior to posteriorly-directed (Stage II) transport.[31] In each chewing cycle, the tongue cycles forward and downward carrying food on its surface. This forward thrust leads to a build-up of triturated food at the front of the mouth. This 'swallowable' material is then moved towards the oropharynx by an upward and posterior sweep of the tongue pressing against the hard palate ('squeeze-back').[30] The tongue and jaw movements are accompanied by complementary movements of the hyoid bone.[36]

All these movements of the tongue and the changing configurations of the floor of the mouth and oral vestibule can contribute to denture instability during feeding and therefore should be taken into account during denture construction.

Stage II transport

Masticated food is moved distally to the posterior surface of the tongue by Stage II transport. The forward movement of the tongue during the occlusal and initial opening phases creates a contact between the tongue and the hard palate. The contact zone moves progressively backwards, squeezing the processed food through the fauces – the so-called 'squeeze-back' mechanism.[30] This material accumulates on the pharyngeal surface of the tongue and in the valleculae, and remains there until swallowing occurs (Figures 6 and 7). During processing of solid foods, the mouth is continuous with the oropharynx;[30] this fact is at odds with the traditional belief (based on descriptions of liquid command swallows – see below) that there is a posterior oral seal during feeding, whereby the mouth and pharynx are separated by the lowering of the soft palate on to the posterior surface of the tongue. A posterior oral seal may be produced during the ingestion of liquids – thereby confining them to the oral cavity proper prior to swallowing. As described below, liquids are swallowed from the mouth (ie without Stage II

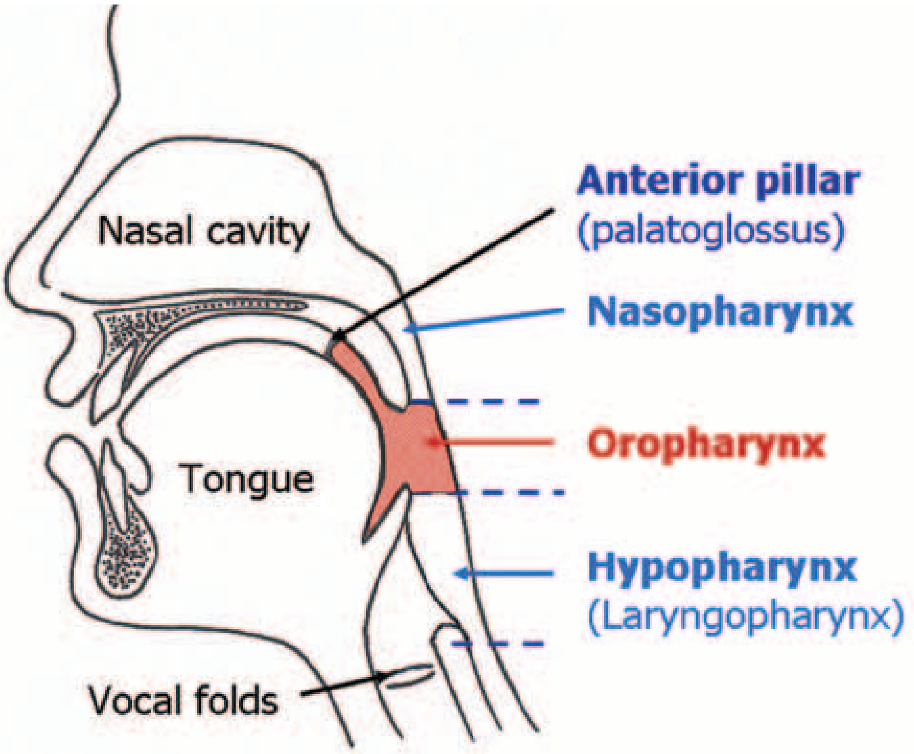

Figure 6. Anatomy of the mouth and pharynx in a human adult. The oropharynx (stipple) extends forward to the anterior pillar of the fauces (palatoglossal arch) and includes the posterior one-third of the tongue.

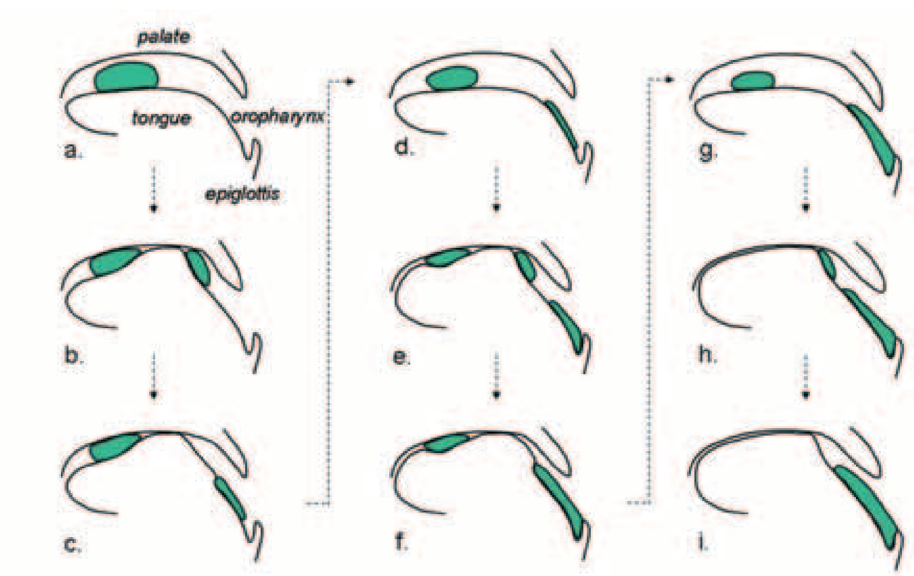

Figure 7. Diagrammatic representation of cyclical tongue movements in Stage 2 transport. Sequence shows how a mouthful of food is broken into smaller pieces which are transported posteriorly on the dorsum of the tongue to the oropharynx (based loosely on videofluorographic records in Hiiemae and Palmer[30]).

transport), whereas solids are swallowed from both the mouth and the oropharynx.

In some cases, especially with large mouthfuls of food, swallowing cycles are interspersed among chewing and transport cycles.[29] For each bolus, the feeding sequence is completed by a terminal or 'clearance' swallow, in which the last remaining pieces of food are gathered and removed from the mouth and oropharynx.

Swallowing

Much of our knowledge of human swallowing derives from observations made on individuals swallowing liquids 'on command'.[37] In such 'command' swallows, liquid 'boluses' are contained in the mouth by both *anterior* and *posterior oral seals* (see above). When swallowing is initiated, the liquid is propelled past the fauces, through the oropharynx and hypopharynx (laryngopharynx) and then into the oesophagus. This description of liquid swallowing is the basis of the traditional textbook subdivision of swallowing into three phases:

- Oral;
- Pharyngeal; and
- Oesophageal.

These phases are defined by the position of the liquid 'bolus' at any one time. However, while the traditional, three-phase account is applicable to liquid swallows, it does not apply as perfectly to solid foods.[38]

Indeed, the transport of solids and liquids are different in several respects. Liquids do not require chewing and so, unless we choose to hold them in the mouth before swallowing, their transport is continuous. Solids, on the other hand, are chewed and can (in part) be transported through the fauces to the posterior surface of the tongue before swallowing. Many textbook accounts give the misleading impression that a food bolus is a neatly circumscribed mass of material. In reality, the masticated material is smeared over a considerable area of mucosa, both in the mouth and oropharynx. One only has to open the mouth during eating to confirm this.

Triturated food accumulates on the pharyngeal surface of the tongue after passing through the fauces[30] (Figure 7). Eventually, an oropharyngeal bolus is generated by the aggregation of this food at the back of the tongue with other food passing from the mouth during subsequent Stage II transport cycles. Normally, the bolus to be swallowed is finally formed in the lower oropharynx and then propelled through the hypopharynx into the opened upper oesophageal sphincter. Thus, it appears that there is no uniquely *oral* phase in the swallowing of solid foods. If one defines the swallowing phase by the position of the bolus, the initial phase of swallowing solids might be better described as an *oral and oropharyngeal phase*. This oropharyngeal bolus is propelled rapidly through the hypopharynx/laryngopharynx, past the laryngeal inlet and through the upper oesophageal sphincter which opens to receive it.

The essential difference between swallowing liquids and solids is that liquids are swallowed from the mouth proper; solids are swallowed from the mouth and/or oropharynx. Thus, during what might be called the 'pharyngeal phase', liquids are propelled through the oropharynx and hypopharynx into the oesophagus, while solids – much or all of which are already in the oropharynx – are propelled through the hypopharynx to the oesophagus. The time for the food bolus to move from the lower oropharynx (posterior tongue-vallecula) to the oesophagus – the 'hypopharyngeal transit time' – is very short (<0.5 sec) and is similar for different foods.[30] The hypopharyngeal transit is the critical period in swallowing, as this is when the bolus is passing the laryngeal inlet, and when the danger of aspiration is greatest.

During this period of pharyngeal transit, various mechanisms act to prevent food entering the airway. These include: apnoea, upward and forward movement of the hyoid-laryngeal complex and closure of the laryngeal inlet (involving depression of the epiglottis and adduction of the vocal folds).[38]

The final part of swallowing is the *oesophageal phase*, which consists sequentially of:

- The opening of the upper oesophageal sphincter;
- Peristaltic waves passing down the oesophagus;
- The opening of the lower oesophageal sphincter;
- The closing of the sphincters.

This phase is much slower and can take 5–12 seconds.[39] The peristaltic wave which moves the bolus is sometimes referred to as the *primary peristalsis* of the oesophagus, to distinguish it from the secondary peristaltic waves which occur subsequently and are generally believed to have the role of clearing the oesophagus of material which has been left behind by primary peristalsis or which has entered the oesophagus by gastric reflux. In human beings, movement of material through the oesophagus is usually assisted by gravity, which can result in the bolus arriving at the lower sphincter before it opens, which happens only after the peristaltic wave arrives.[39] In fact, some animals, eg giraffes, swallow 'uphill', or at least horizontally, and human beings can swallow while upside-down, which demonstrates the effectiveness of the peristaltic forces and the integrity of the various mechanisms preventing reflux. In contrast to peristalsis in lower parts of the gastrointestinal tract, peristalsis in the oesophagus consists only of a contraction of the muscles behind the bolus; there is no muscular relaxation in front of the bolus, as occurs in the intestine, although this may reflect the fact that the oesophagus has little or no muscular tone.[40]

The likely control mechanisms for mastication and swallowing are dealt with in the next article in this series.[41]

Acknowledgement

The authors wish to dedicate this paper to the memory of Dr Karen Hiiemae whose research changed our understanding of the relationship between mastication and swallowing and who kindly advised us on an early draft of this manuscript.

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Abstract

DO YOU PRESCRIBE ALCOHOL TO YOUR PATIENTS?

The role of alcohol in oral carcinogenesis with particular reference to alcohol-containing mouthwashes. McCullough MJ, Farah CS. *Australian Dental Journal* 2008; **53**: 302–305.

This paper reviews the literature relating to alcohol and oral cancer, and especially the limited published work on the effect of alcohol-containing mouthwashes. It appears that, until recently, there was a known but not statistically significant aetiological connection. However, a recent paper by Guha *et al*, reporting an extensive study, has now shown a significant link between the daily use of alcohol-containing mouthwashes and the disease. In conjunction with the twice daily use of these medicaments, those who were also smokers suffered a nine-fold (9.12) increase in their risk of acquiring oral cancer, those who also drank alcohol suffered a five-fold (5.12) increase, and even patients with no other risk factor habits showed an increased risk of almost five times (4.96).

The authors point out that, whilst many of these products have been shown to be effective in penetrating oral biofilms and reducing bacterial load, it would be wise to restrict their use to short term therapeutic situations. Indeed, like other medication, mouthwashes should only be used under written and detailed prescription from a dental practitioner for short periods and specific reasons. They conclude that, in their opinion, it is inadvisable for healthcare professionals to recommend the long-term use of alcohol-containing mouthwashes.

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CPD ANSWERS

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1. A, B, C
2. A, C, D
3. A, B
4. A, B, C
5. C, D
6. A, D
7. A, B, C
8. B D
9. A, B, C
10. B, C, D