Journal of Oral Rehabilitation 2006 **33**; 840–849

Review Article
The regulation of masticatory function and food bolus formation

A. WODA*, A. MISHELLANY*, M-A. PEYRON† *DIDO, EA 3847, Faculté Dentaire, Université d'Auvergne, Clermont-Ferrand, France and †INRA, Theix, Saint-Genès-Champanelle, France

SUMMARY This review emphasizes the following points:
1 The values of the physiological parameters of mastication (number of cycles and total electromyographic activity in the sequence, sequence duration, cycle frequency in the sequence, kinetic characteristics of the cycles) are characteristic of each individual and vary widely from one individual to another. In a given individual their modification reflects an adaptation of mastication to the size of the food bolus, and the hardness and rheological characteristics of the food.
2 The ready-to-swallow food boluses produced by different individuals nevertheless display similar particle size distributions.
3 Ageing entails adaptation of the masticatory function and does not impair swallowing.
4 Observed increase in total electromyographic activity shows that more energy is expended in mastication by full denture wearers. Despite this increased muscle activity, loss of teeth, even if compensated for by complete dentures, hinders the formation of a normal bolus. The food boluses made by denture wearers thus contain many large-size particles. The impaired mastication observed in denture wearers approaches the masticatory disabilities found in persons with neuromotor deficiencies.
KEYWORDS: ageing, electromyography, food bolus, full denture, granulometry, mastication

Accepted for publication 14 January 2006

Introduction

The experimental findings presented in this review respond to the following questions. What is the particle size of the food bolus before swallowing? How does mastication adapt to food texture, mouthful size, ageing and the wearing of complete dentures so as to reach the desired pre-swallow food bolus particle size?

The clinical aim of restoring masticatory function is most often no more than a delusion. Only anatomical restoration is usually achieved because in practice no methods are available to assess function. Function first has to be fully describable before it can be evaluated and then restored. Work to gain a better understanding of the physiology of mastication has therefore been undertaken by several groups throughout the world and some of the most significant results are reported in this short review.

It is generally acknowledged that during a meal the food is eaten in mouthfuls and the processing of a mouthful involves a mastication sequence, itself made up of some 10–40 chewing cycles.

Physiology of mastication in healthy young subjects

Studies of the physiology of mastication have been carried out using two main tools: kinesiography for recording jaw movements and electromyography for

The present paper is based on a lecture presented at the International meeting on Advances in Oral Physiopathology: From basic research to clinical implication, held in Turin, December 9–11, 2004.

 doi: 10.1111/j.1365-2842.2006.01626.x

recording muscle activities. Jaw movements have been recorded by different techniques, those most frequently used being based on the production of a magnetic field (1), the detection of a moving light attached to the tissues overlaying facial bones (2), the use of infrared-emitting diodes (3) or videographic recording (4). In our group, sub miniature coils attached to teeth are used to measure the amplitude of electromagnetic signals.

Electromyographic (EMG) activity was generally recorded on the four easily accessible elevator muscles of the mandible (5, 6), the left and right temporal and masseter muscles. In these studies, many different sets of variables were used, but those most commonly measured were vertical and lateral movement amplitudes, number of cycles in the sequence and the duration of the sequence. As the area under the EMG activity curve is directly related to the work done or the energy expended, the area under the EMG activity curve for one cycle and for the entire sequence was frequently considered. The cycle frequency in the sequence was also often calculated. An example of the kinesiographic and EMG recordings is shown in Fig. 1a, which depicts the mandibular movement in the frontal plane, which classically follows a drop-shaped path. The path of a mandibular incisor during a complete sequence can be broken down into 10–20 successive cycles, each characterized by a downward movement followed by an upward movement. The graphs in Fig. 1b show the time course of the successive mandibular cycles. EMG recordings of the masseter show that this muscle is active when the mandible moves upwards to crush the food.

The first important finding obtained using these tools was that all these parameters displayed very high interindividual variability (1, 7). In other words, for a given food the mastication cycle was highly characteristic of each individual. For example, Fig. 2 shows the mastication pattern displayed by two different individuals chewing the same food. These two subjects had the same age and similar morphological characteristics, including similar dentition, and yet they showed markedly different mastication characteristics with, for example, a large difference in the number of cycles per sequence. The origin of this inter-individual variability is not fully known. It has been argued that it might reflect morphological differences in the masticatory system such as a unique anatomical relationship between the muscles, bones and teeth, but the observed differences in mastication patterns are only weakly related to characteristics of dentition, contrary to what might be expected (8).

The influence of the size of the mouthful has been studied with many different kinds of natural, artificial or fake foods (9–14). An increased mouthful size causes an increase in several parameters, but mainly vertical amplitude of the mandibular movements (9, 11, 14). The influence of the hardness of the food and of its rheological characteristics was tested in other experiments. Initially, most authors used natural foods sometimes placed on a graded scale to vary food

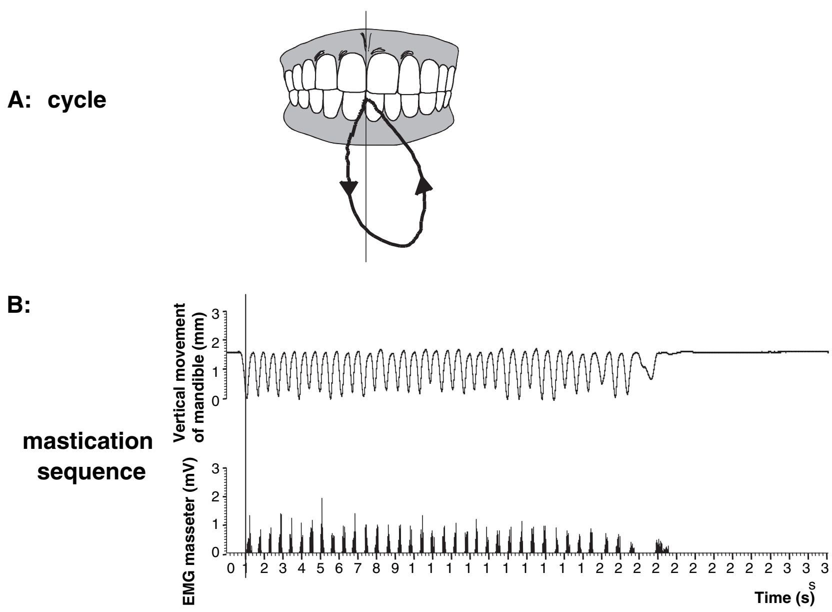

Fig. 1. (a) Path of the mandibular inter-incisive midpoint in the frontal plane during a mastication cycle. (b) Example of a recording of the vertical displacement of the mandible against time during a complete mastication cycle (top) together with an EMG recording for the masseter muscle (bottom).

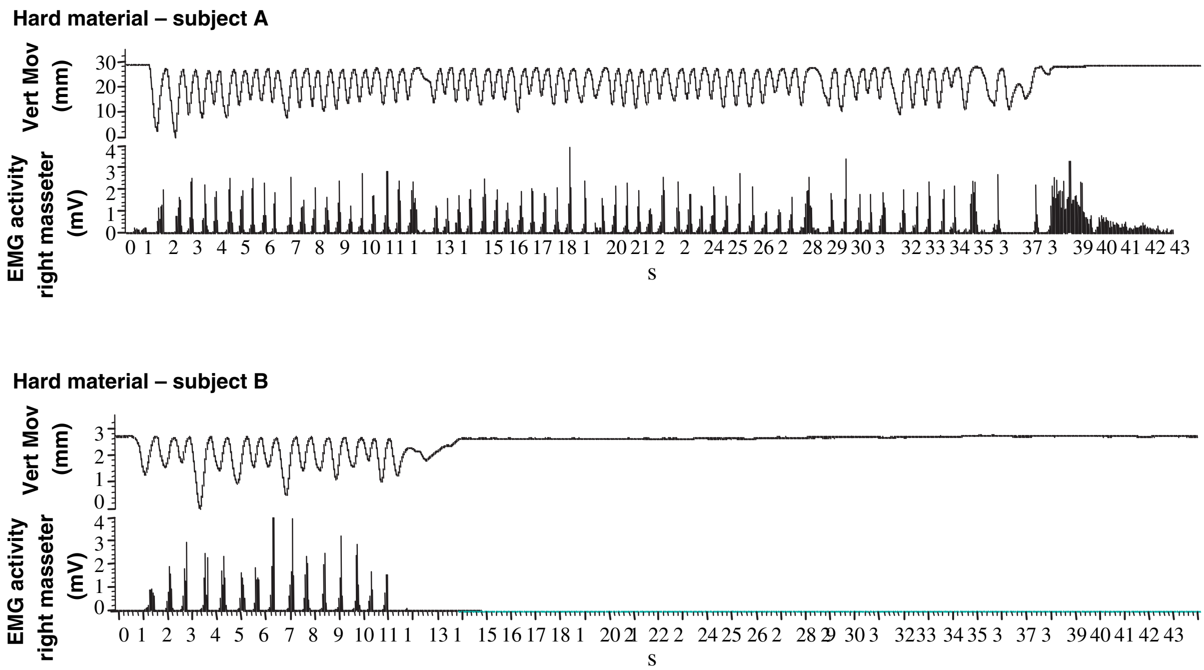

Fig. 2. Example of inter-individual variability for EMG recordings and vertical displacement of the mandible in two subjects A and B during a complete sequence of mastication of a hard elastic model food.

hardness. Hardness is, however, a loose term that covers many different food properties such as elasticity, plasticity, toughness, viscosity and brittleness (15–19). To control these food properties better, non-alimentary models usually made with elastomers were used (5, 20, 21). As they are impossible to swallow, their use limits the observation of natural chewing and they have been mostly used in masticatory efficiency testing (22, 23) and as such, frequently and usefully employed in a clinical context (24, 25). Laboratory-made model foods have recently been introduced to replace artificial foods (7). These edible materials offer the advantage of possessing consistent mechanical properties; they are essentially elastic or plastic materials and can be made with ranging hardness. It is thus possible to dissociate masticatory adaptations due to hardness from those due to food texture. These foods resemble commercial confectionery products. Their use enables us to discern the relative roles of hardness versus texture in the course of masticatory adaptation to the food. Increased hardness results in an increased EMG activity during each cycle and a greater number of cycles per sequence (26). Switching from an elastic to a plastic food results in a change in the cycle pattern, which among other features shows increased amplitude of both vertical and lateral mandibular movements (27).

Particle size in food boluses of healthy young subjects

Another approach to the study of mastication is to focus on the food bolus that is the end result of the process. Through the insalivation and comminution of the food, mastication serves to form a food bolus that must be plastic, well lubricated and above all cohesive in order to be swallowed easily (28). Cohesiveness is most important: the bolus must behave as a single unit and not break up spontaneously (28, 29). Before the food bolus enters the oesophagus, it is vital that the food particles are not dispersed in different directions. The importance of this condition is illustrated by the high morbidity and mortality among older dependent persons because of food 'going down the wrong way'. Aspiration of food particles is in particular one cause of chronic pneumonia (30–34). It is thus essential that mastication should successfully produce a well-formed bolus that is above all cohesive. It is now apparent that swallowing is triggered when a certain threshold is reached, which depends on both lubrication of the food bolus and the food particle size (28, 35–38) for many types of food, and on plasticity for meat (39). The perception of the resulting bolus cohesion and plasticity may in turn be the key signal that informs the swallowing centre of the need to operate and trigger a safe swallow.

Observation of the distribution of particle size has been the most common method to analyse the food bolus. Despite its relevance, the plasticity of the food bolus has not been measured, probably because of technical difficulties. The methods used to measure particle size have included microscopy and image analysis, sedimentation analysis, diffusion of light, sieving and laser diffraction (40–44). Figure 3 schematizes three of the most used methods. They all require the subject to expectorate the bolus just before it is going to be swallowed. The bolus can then be dried and fractionated by serial sieving or analysed by examining particle size by optical microscopy and using image analysis software. The bolus can also be suspended in a liquid and illuminated by a laser; the diffraction angle of the beam depends on particle size, and so gives a measure of particle diameter. These different methods consistently yielded an important result: despite marked differences in particle size distribution from one food to another, for a given food, all the subjects studied in the different experiments produced a bolus with approximately the same particle size distribution (10, 45, 46). This finding can be interpreted as demonstrating the need to obtain a fully masticated bolus that can be safely swallowed.

This observation contrasts sharply with the already noted very high variability of most of the mastication parameters, such as the number of cycles per sequence, the duration of the sequence, the amplitude of mandibular movements, the cycle pattern, or the degree of EMG activity during each cycle. The paradox of high variability of masticatory parameters versus relative similarity for the food bolus particle size or shape strongly suggests that all healthy, normal-dentate subjects use varied strategies for mastication, but chew the bolus so as to obtain a set degree of comminution, similar for everyone. The correlate is that a decreased efficiency in the food breakdown can be offset, at least within certain limits, by an adaptation of the physiological parameters of mastication. Therefore, it is clear that each individual variously uses his or her masticatory apparatus, habits and learned chewing behaviour in such a way as to ensure that each food bolus can be swallowed safely, with minimal risk of aspiration.

Effects of ageing on the kinetics and EMG parameters of mastication

The effect of ageing was first observed with natural foods. Older subjects were found to increase the number of cycles and the sequence duration during mastication of carrots (35). The effect of ageing was also observed with kinetics and EMG recordings while chewing and swallowing elastic model foods (47). The results are shown in Fig. 4. Each of the 67 subjects is represented by a point located according to age and the number of cycles required to chew and swallow the model food. The regression slope in the figure shows an increase of about 50% in the number of cycles between the youngest and the oldest subjects. Hence ageing causes an increase in

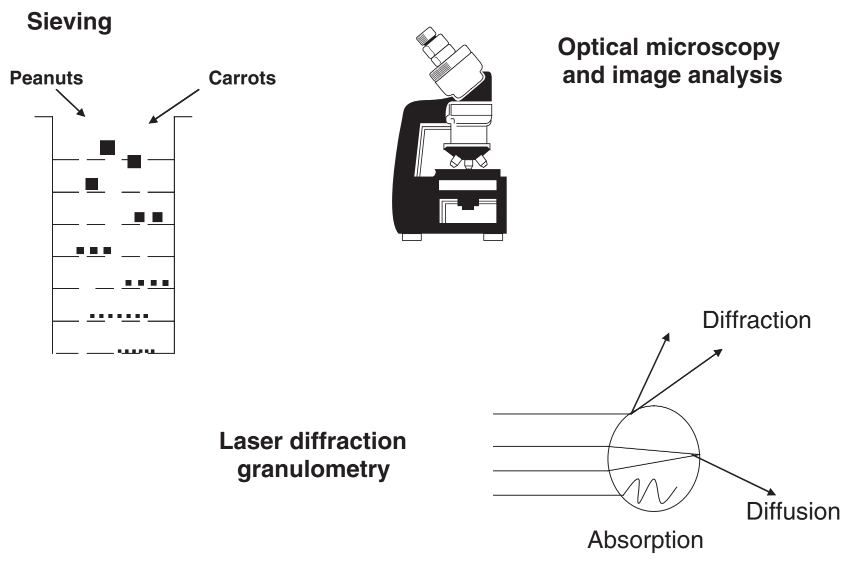

Fig. 3. Three methods for measuring particle size distribution in the food bolus were used. In all cases the bolus was recovered just before swallowing. Determination of the particle sizes by sieving is the more common method. Seven sieves were used in our experiments. Of the several ways in which a laser beam interacts with suspended particles, only diffraction was used because diffraction angle depends on the particle diameter. Examination by optical microscopy was coupled with computer-aided analysis of particle shape.

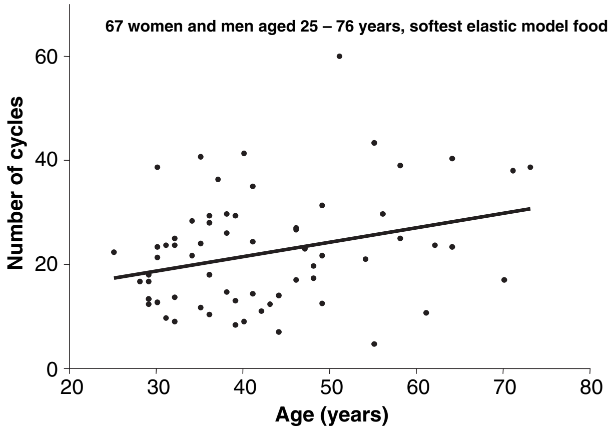

Fig. 4. Effect of age on the number of masticatory cycles performed during mastication of four foods with the same rheology but with gradually increasing hardness. Only the points representing data collected for the softest elastic model food for each subject regression line are represented here. Linear regression analysis showed that the total number of cycles in a sequence increased significantly with the hardness of the food ($P = 0{\cdot}0001$) and with age ($P = 0{\cdot}0001$), but that gender had no effect ($P = 0{\cdot}202$) (47).

the number of cycles. The study also showed that the elderly were able to compensate for changes in food hardness in the same way as younger subjects, as mastication of harder model foods showed the same pattern, but with a larger number of cycles.

Although both muscle mass (48) and maximal bite force (49–51) are known to decrease with age, the increase in the number of cycles was paralleled by an increase in the total amount of EMG activity throughout the masticatory sequence (47). This suggests that the surface area of muscle fibres contracting during the burst is approximately constant during ageing and that the proportion of motor units used during the chewing of a standard food product compared with the total available number of motor units must increase gradually with age. Therefore, the jaw closing muscles of older people are probably working closer to their maximum capacity than those of the young. In other words, ageing is accompanied by an increase in EMG activity, i.e. increased energy expenditure by muscles to produce a food bolus that can be safely swallowed. The same type of comparison between young and older subjects was made in another study, this time with natural foods, namely peanuts and carrots (52). The main results are shown in Fig. 5a and b. With peanuts the same marked increase in number of cycles, sequence duration and EMG activity per sequence was observed. Similarly, there were no significant changes in either EMG activity per cycle or cycle frequency. The same conclusions could be drawn after mastication of a harder food such as carrot. During ageing the number of cycles increases, and older people expend more energy, use more cycles and take more time to produce a food bolus.

Effect of ageing on food bolus particle size

It must be borne in mind that the observations described above concern only variables characterizing the physiology of mastication. They do not say that the food boluses produced by young and older people are identical. If confounding factors such as missing teeth are controlled for, ageing alone has little impact on the ability of subjects to reduce food into small particles (35, 51, 53–55). Figure 5c and d show the particle size distribution in these two groups, measured by sieving. The older subjects, when they chewed peanuts, made more small particles and fewer large ones. This shift was even more pronounced with carrot. In other words, older persons produce a bolus of somewhat better quality, with finer particles, than young subjects. Thus older persons not only achieve the same result after mastication as younger subjects; they actually go further and produce a better bolus in terms of particle size distribution, despite an extra energy cost reflected in an increased EMG activity per sequence. The reason for this unexpected effect is unclear, but we can conclude that ageing brings an adaptation of mastication, but no masticatory disability. Thus the purpose of chewing, which is to make a smooth, plastic and cohesive food bolus (28), is still achieved despite ageing of the masticatory apparatus.

Number of cycles, EMG activity and sequence duration are further increased as mastication efficiency is decreased in complete denture wearers

Denture wearers strive to adapt to their masticatory apparatus deficiency as reflected in an increase in the number of chewing cycles, duration of mastication sequence and EMG activity per sequence (5, 56–58) Figure 6 shows the results of mastication of peanuts and carrots in fully dentate and denture-wearing subjects of the same age. The values of mastication

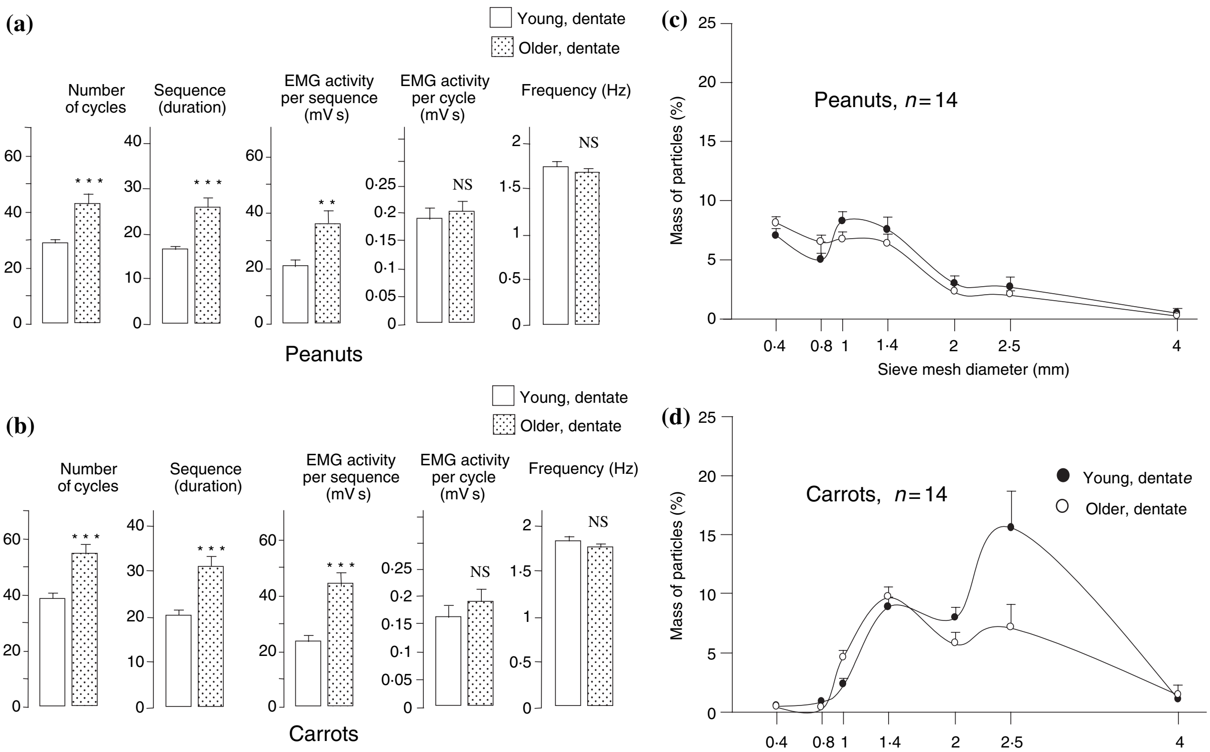

Fig. 5. Principal variables measured in an EMG recording during mastication of two foods (peanuts and carrot) [(a) and (b)] and corresponding particle size distributions [(c) and (d)] in two populations (young dentate, older dentate). Average (±s.e.) of 14 subjects observed in each groups. One-way ANOVA in (a) and (b) and two two-way ANOVAS in (c) and (d). A significant interaction between sieve and group factors indicated that the particle size distribution was significantly different (df = 6, $P < 0{\cdot}001$) for both peanuts ($F = 5{\cdot}8$) and carrots ($F = 20{\cdot}6$).

parameters reached higher levels than those observed in aged fully dentate subjects even with an easy-to-chew food such as peanut (Fig. 6a). The edentate subjects thus expended more energy chewing than their fully dentate coevals. Their EMG activity during the cycle was not significantly increased, and the cycle frequency was unchanged. However, with food that was more difficult to chew, such as raw carrot, an additional increase in the energy expended during the sequence was observed compared with dentate coevals (Fig. 6b). Most importantly, the frequency was this time reduced very significantly. It must be noted that despite this increased energy expenditure, the goal of mastication was not totally reached. Indeed many studies report that masticatory efficiency was decreased by 50–85% compared with subjects with intact dentition (54, 57, 59–61) and that denture wearers made a much coarser bolus than dentate subjects (5, 53, 55). Figure 6c and d indicate a marked fall in bolus quality as measured by particle size distribution. With both peanuts and carrots, the sizes of particles swallowed by the complete denture wearers were markedly greater than those swallowed by the two groups of dentate subjects. Hence denture wearers are appreciably disabled as regards masticatory function in that they do not seem to be able to produce a satisfactory food bolus. They lie outside the range of normal adaptation if the aim of mastication is taken to be the production of a food bolus with sufficiently small particles. This impairment was not because of a decreased of saliva flow, because fully dentate or denture-wearing subjects presented the same stimulated or spontaneous saliva flow rate as young subjects (62, 63). A modification in the saliva composition could not, however, be ruled out (64).

Mastication appears to be even more difficult when the denture wearers eat meat. This was tested by giving six meat samples of increasing hardness (65). Whereas dentate subjects adapted their total EMG activity during the sequence to the food hardness, the denture wearers were unable to do so (Fig. 7). They failed completely to adapt to the greater hardness

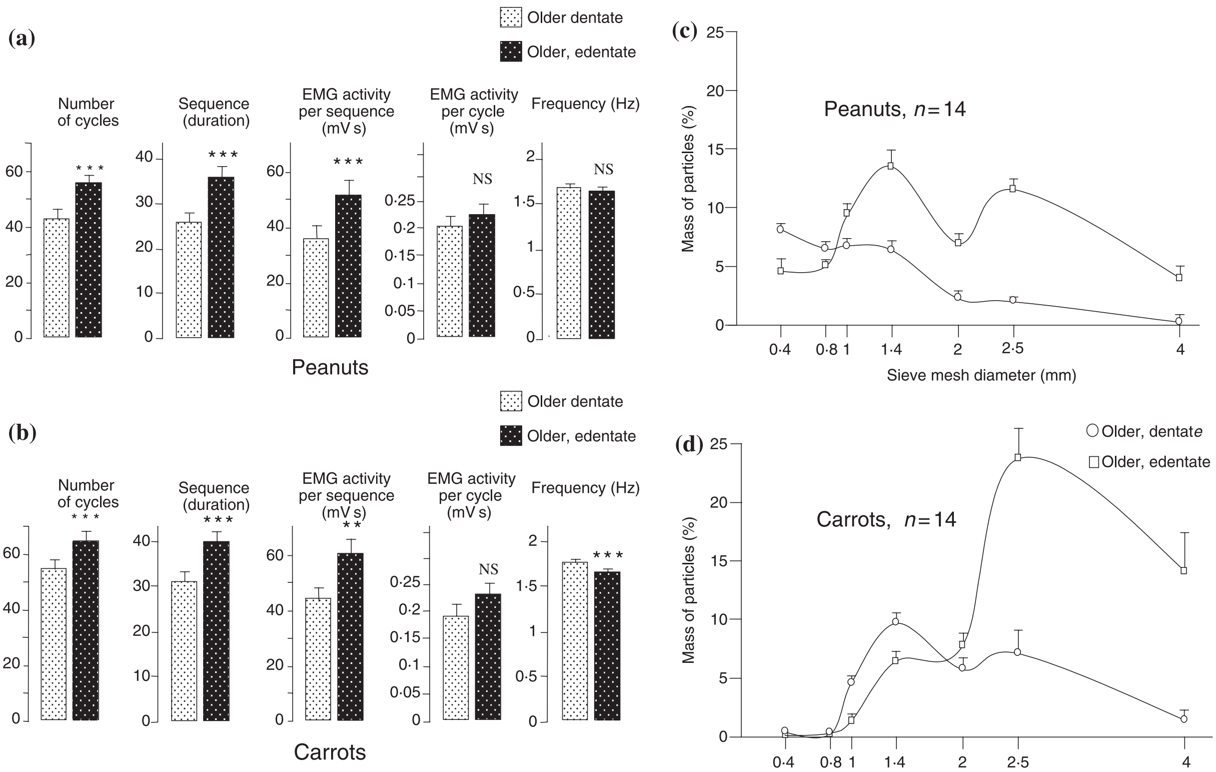

Fig. 6. Principal variables measured in an EMG recording during mastication of two foods (peanuts and carrot) [(a) and (b)] and corresponding particle size distributions [(c) and (d)] in two populations (older dentate and older edentate denture wearers). Average (±s.e.) of 14 subjects observed in each group. Unlike older dentate persons whose mastication can adapt to produce a satisfactory food bolus, edentate denture wearers do not manage to produce a sufficiently well prepared food bolus. One-way ANOVA in (a) and (b) and two two-way ANOVAS in (c) and (d). A significant interaction between sieve and group factors indicated the particle size distribution was significantly different (df = 6, $P < 0{\cdot}001$) for both peanuts ($F = 60{\cdot}4$) and carrots ($F = 83{\cdot}6$).

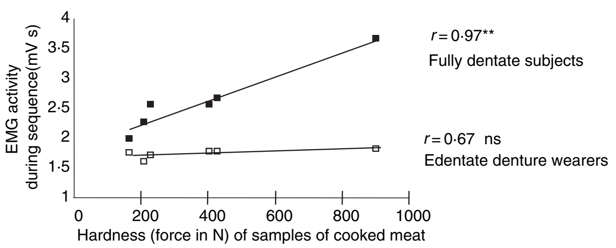

Fig. 7. Effect of increasing the hardness of meat samples masticated by older fully dentate subjects and edentate denture wearers [from Veyrune and Mioche (65)].

levels and even tended to refuse mastication altogether. Thus mastication is genuinely impaired in complete denture wearers. Similarly, decreased masticatory performance or impaired chewing function have been described in subjects with either dental malocclusion (25, 66) or temporo-mandibular disorders (67).

Severe disablement of the masticatory function

A further level of disability can be observed with neuromotor deficiencies in Alzheimer patients, dependent elderly persons, Down's syndrome, and generally in a wide range of neurological illnesses. The mastication of Down subjects was observed by videoscopic monitoring. This method, which has been validated (4, 68), can be most useful because it is very simple and can be applied in clinical conditions outside a laboratory. It showed that for most foods, mastication of persons with Down syndrome was appreciably impaired, and many foods were hardly chewed or not chewed at all. In addition, the cycle frequency was strongly reduced compared with controls. This finding points to a severe disablement of the masticatory function (69). EMG recordings also point to an almost complete desynchronization of mastication with near-total loss of its cyclic pattern (70). In both Down patients and edentate subjects, masticatory disability leads them to swallow food that is inadequately prepared and/or to change their diet. They prefer softer, more thoroughly cooked foods, often industrially processed, and turn away from fresh fruit and vegetables, and meat that requires vigorous mastication. The consequence in all cases may be reduced nutrient availability [see references in (47, 71, 72)].

Acknowledgments

We are indebted to Richard Ryan for language editing and to the organisers of the symposium: Advances in Oral Physiopathology, Turin 2004, where this presentation was given.

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Correspondence: Alain Woda, Faculty of Odontology, 11 bd Charles-de-Gaulle, 63000 Clermont-Ferrand, France.
E-mail: alain.woda@u-clermont1.fr