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Food Crushing Sounds. An Introductory Study[a,b]

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SUMMARY

The sounds produced by chewing foodstuffs, or by crushing them between flat surfaces, were tape recorded and analyzed as to amplitude, frequency, and duration. Preliminary data are given on chewing sound characteristics, including certain differences between foodstuffs.

An appreciable part of the literature of food rheology is devoted to the measurement of the slowly varying forces necessary to crush foodstuffs (Kramer and Twigg, 1959). Biting forces (Howell and Manly, 1948; Potter *et al.*, 1947), jaw movements during chewing (Klatsky, 1940; Klatsky and Fisher, 1953), and relations between jaw positions and various aspects of hearing (von Békésy, 1932, 1939; Franke *et al.*, 1952) have also been studied. However, only little attention has been given to vibrations produced by the action of the complicated feedback mechanism that regulates the rate and force and duration of chewing.

The possibility exists that physical measurements of crushing sounds could be helpful in the field of food texture by providing new information to correlate with sensory data. As an introduction to such work, this paper is concerned with the development of methodology and with a study of relevant variables.

METHODS

Apparatus. The equipment consisted of the following components, which were used to obtain strip-chart recordings of sound spectra and of amplitude variations with time.

For sensing of sounds. The sound pick-up device was a dynamic microphone of a low-impedance directional type (Signal Corps, U. S. Army, M-44A/U) or a hearing-aid earphone of a high-impedance extended-range type (Dyna-Lab, similar to Danavox DT). In an attempt to isolate the body of the earphone from vibrational contact with the head of the chewing subject, it was connected to the ear canal via a short plastic tubing.

For tape recording and reproduction of sounds. The recorders were: 1) a sound recorder-reproducer set for 2400 feet of ¼-inch half-track magnetic tape with speeds of 15 and 7½ inches per second, and provided with a spring-loaded pulley so that endless tape loops could be used instead of conventional continuous (nonloop) tape; 2) a less versatile sound recorder-reproducer with speeds of 7½ and 3¾ inches per second. (Signal Corps, U. S. Army, respectively, AN/TNH-2A and RD-87A/U for 1) and 2); both manufactured by Telectro Industries Corp., Long Island City, N. Y.)

For frequency analysis. Used for frequency analysis was the audio spectrometer part (Model No. 2109) of an automatic spectrum recorder with 31 channels, of which 27 gave 1/3-octave bands for the range 40–16000 c/s, 3 gave weighted responses corresponding to standards for objective sound-level meters, and one gave a linear response corresponding to the total sound (Brüel & Kjaer, Copenhagen, Denmark, Model 2311).

For strip-chart recording of amplitude data. Used for strip-chart recording were: 1) a vacuum-tube voltmeter with instrument terminals

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carrying a DC component (Voltohmyst WV-87B or WV-77E). 2) An attenuator consisting of a decade resistance box in series with two resistors of 33 and 6.8 kilo-ohms. The output to the strip-chart recorder was the terminals of the box, which was usually positioned at values ranging from 300 to 3000 ohms. The series combination of the box and the 6.8 kilo-ohms resistor could, when desired, be shunted with a 100-microfarad electrolytic capacitor. 3) A strip-chart recorder for 1 mV DC with 1-second full-scale pen travel (Model 143X58, Electronik, Minneapolis-Honeywell Regulator Co.).

For auxiliary purposes. Also used were: 1) a dual-beam cathode-ray oscillograph (Type 322-A, Du Mont), which was usually connected to the input and the output of the frequency analyzer; and 2) an audio generator (Sine-Square Wave Generator, Model AG-10, Heathkit).

Foodstuffs. During initial stages cookies, crackers, potato chips, apples, and chewing gums were used. Later work was performed mostly with crisp bread (Swedish-style "Knäckebröd," brown, and "Delikatess," white), beef, apple, crisp head lettuce, and peanuts. Tenderness-rated dehydrated beef had been prepared at the Institute. The other foodstuffs were commercial products.

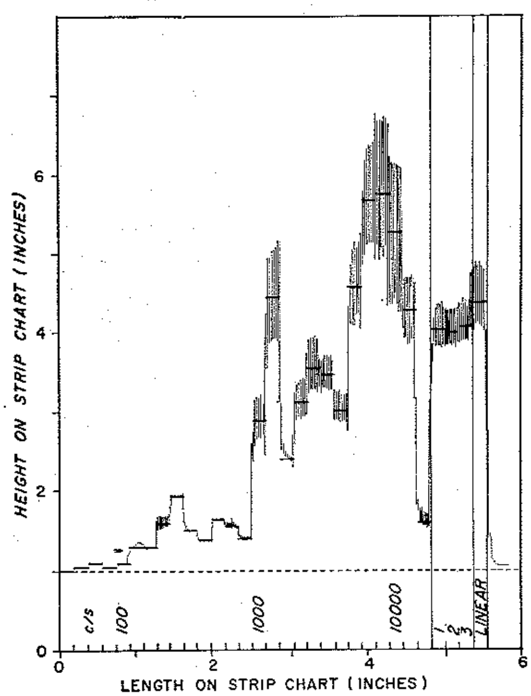

Fig. 1. A typical recording of a chewing-sound spectrum (for crisp brown bread; "open mouth" technique) with visually estimated mean values marked as horizontal lines. Along the abscissa, from left to right: 27 frequency bands, centered on frequencies from 40 to 16000 c/s; 3 weighted responses; one linear response.

Techniques. There are, principally, two different ways of using a tape recorder in combination with a frequency analyzer. One is to use an endless loop of tape, so that the playback of a short recording can be frequently repeated while the frequency analyzer sweeps over a series of bands, and the other is to run the recorder in the regular (nonloop) way. In the first case, the strip-chart record gives a sound-amplitude spectrum that, with a frequency analyzer having discrete bands, will appear step-shaped (*cf.* Fig. 1). In the latter case, a continuous strip-chart recording has to be made for every frequency band of interest (*cf.* Fig. 11). The first method gives "time average" data, whereas the latter gives "time course" data.

Application of sensing device. While the subjects chewed a piece of food, the mastication sounds were taken off by one of the following methods: a) The microphone was pressed against the cheek on the side where chewing was done; b) the microphone was held 2 inches in front of the open mouth, while the subject chewed between the front teeth, or c) the plug of the earphone was inserted into one ear canal in such a way as to close the orifice to the outer air, while the subject chewed on the side where the earphone was held. In some cases, foodstuffs were also pressed between a block of wood and the surface of a table, while the microphone was held 2 inches from the edge of the block. The four methods are respectively referred to herein as "through cheek," "open mouth," "ear canal," and "wood block."

Recording of sounds. When recording on tape loops, 15 inches per second was the usual speed, and the length of the loops was 30 inches, i.e., 2 seconds. The erasing head of the recorder AN/TNH-2A was often disconnected during work with tape loops. This gave a better utilization of the magnetic layer, while at the same time the biasing AC voltage on the recording head was sufficient to give enough erasing action to prevent a serious build-up of several recordings on top of each other. The start and stop of a recording on a tape loop was usually effected by manually closing and opening the shutter that presses the tape against the recorder head. This procedure gave recordings without switch-off clicks, which in preliminary experiments showed up as disturbances in the spectra. To obtain a stable recording level, a constant tone was recorded on available brands of magnetic tape, and those found most homogeneous were selected. Care was taken not to overload the electronic amplifiers. This was especially important since the impact-type sounds of chewing do not ordinarily show up well on the moving-coil instruments of the recorder-reproducer and of the VTVM. All recordings were made in a quiet, but not soundproof, room.

Recordings were usually started with the second or third bite. This was adopted to avoid erratic results from irregular starts of the chewing.

Reproduction of tape records ("playback"). The low-impedance output from the recorder-reproducer was connected through a shielded cable to the amplifier input of the frequency analyzer. For work with tape loops, the latter was run with the automatic sweep, ordinarily set to give a rate of about 8 minutes for all 31 positions. For work with continuous (nonloop) tape, the sweep was, of course, not used. Strip-chart recordings from tape loops were usually made with a paper speed of ⅔ or 2 inches per minute, whereas for continuous tape 2 or 8 inches per minute was used.

In some cases, a tape record obtained at a speed of 15 inches per second was played back at 3¾ inches per second and simultaneously recorded on the other recorder at 15 inches per second. When the new record was played back at 3¾ inches per second to the frequency analyzer, the strip-chart recording was extended 16 times. This procedure gave a better resolution along the time axis, but, of course, some information was lost since the lower part of the original spectrum fell outside the range of the available equipment.

Evaluation of strip-chart recordings. The ordinary way of treating strip-chart recordings was to copy the visually estimated mean for each one of the frequency bands on another paper. The heights were then measured in millimeters and the measured values were transferred to semilogarithmic diagrams. Fig. 1 shows an example of a strip chart recording with mean values marked off.

For continuous-tape (nonloop) records, the strip-chart recordings were either copied and compared visually, or the heights of the peaks were measured, tabulated, and statistically evaluated.

Controls. Three repeated strip-chart recordings of the same tape loop record gave the data in Fig. 2-A, and single strip-chart recordings of three different tape-loop records for the same foodstuff gave the data in Fig. 2-B.

Chattering sounds, produced by rapidly closing the jaws at a steady rate without anything between the teeth, were of much shorter duration than sounds obtained with food. The coefficient of variation (standard deviation divided by the mean) for 35 consecutive peaks was 6% for the total sound and 38%, 28%, and 29%, respectively, for the frequency bands 200, 630, and 2000 c/s.

MEASUREMENTS

Time average experiments. The technique with tape loops was used to obtain information about mastication and crushing-sound characteristics for a number of foodstuffs.

Comparisons between various foodstuffs. At an early stage of this work, a series of foodstuffs were crushed, and the sounds produced were recorded by the following techniques: a) "through cheek," b) "open mouth," and c) "wood block." These experiments gave the data in Fig. 3, in which the points indicate mean values for, usually, 2 or 3 chewings by one person, or 2 or 3 crushings. To take out some of the step-function effect of the frequency bands, all values in Fig. 3 have been smoothed by weighting with ¼ of the two adjacent values.

Comparisons between people. Two series of experiments were performed to estimate the variation of chewing sounds between people.

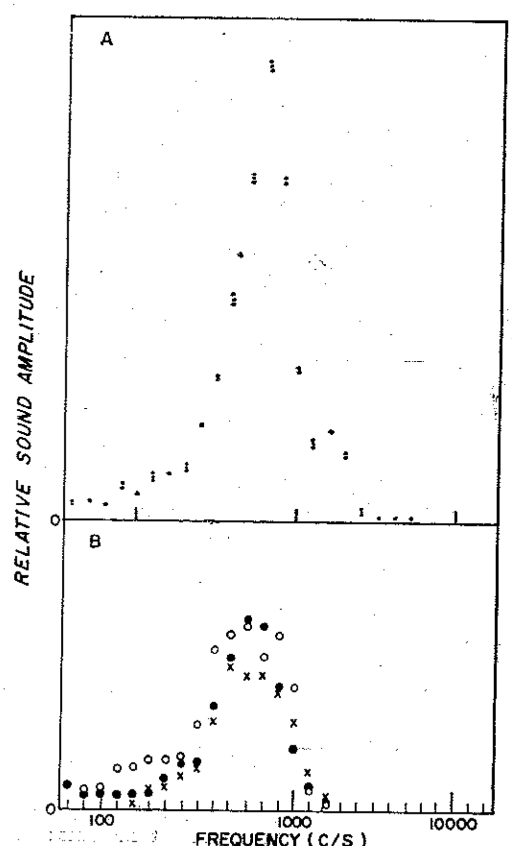

Fig. 2. A) Three chewing-sound spectra obtained from the same tape record (apple, "through cheek" technique); B) three chewing-sound spectra obtained from separate tape records (cookie, "through cheek" technique).

In the first series, crisp brown bread was chewed with the mouth open, 4 times by each of 5 persons, and sound spectra were obtained for the region 800–16000 c/s. Fig. 4 shows that peaks occurred at approximately the same frequencies and had approximately the same heights. However, the dispersion is greater in the region 2000–6300 c/s than at the two peaks at 1250 and 8000 c/s. Also, there is an anomaly at 1000 c/s, where one person showed exceptionally high values (unfortunately, this person was not available for a recheck). The standard deviation of amplitude values was relatively independent of frequencies and persons. The coefficient of variation for the peak values in the vicinity of 10,000 c/s varied between 13 and 31%. An analysis of variance demonstrated a significant difference ($p < 0.05$) between people at 6300 c/s, but not at the frequencies 5000, 8000, and 10000 c/s. The amplitudes for the other frequencies were not considered large enough to warrant a finer analysis.

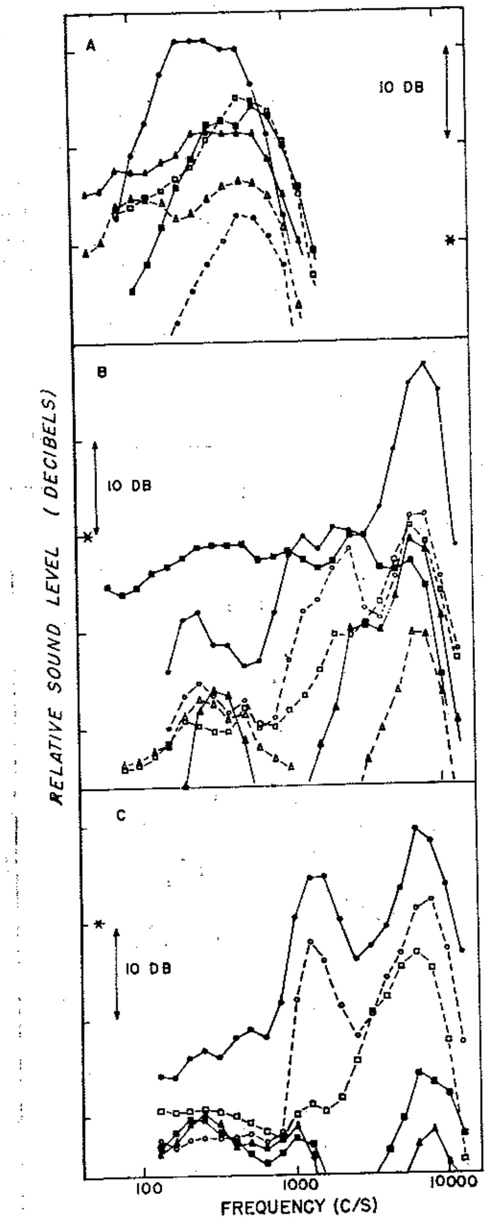

Fig. 3. Chewing-sound spectra obtained for six foodstuffs with the following techniques: A) "through cheek"; B) "open mouth"; and C) "wood block." ○ = crisp white bread; □ = crisp head lettuce; △ = ham; ● = crisp brown bread; ■ = apple; ▲ = sausage. A sound level of 20 db above a "general noise level" is indicated by an asterisk.

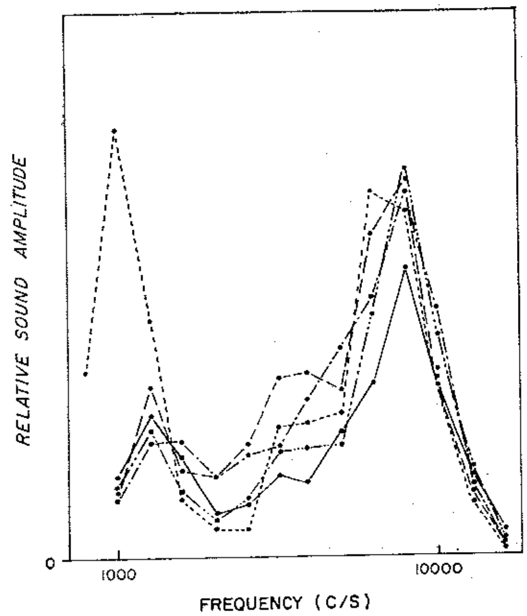

Fig. 4. Sound spectra for 5 persons chewing crisp brown bread ("open mouth" technique). Each point indicates the mean amplitude for four samples.

In the second series, each of 4 persons chewed 4 samples of tough and 4 samples of tender beef, using the "ear canal" technique. Pooled data for each person are plotted in Fig. 5 in the form of a partial spectrum.

Effect of toasting. To obtain a series of foodstuffs differing in only one relevant aspect, soft white bread was toasted to various degrees, and samples were chewed with the "open mouth" technique. This gave spectra of the type shown in Fig. 6. A plotting of peak amplitude values for two persons against degree of browning (measured by a subjective scale) gave the data in Fig. 7.

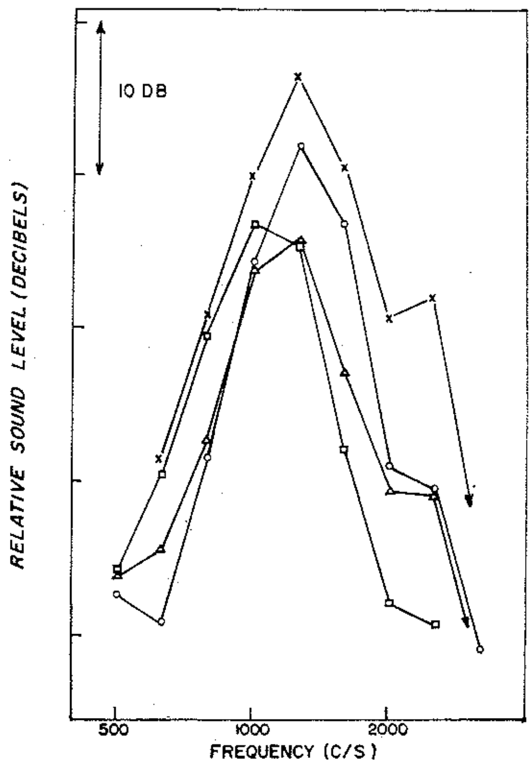

Fig. 5. Spectra for sounds produced by 4 persons chewing beef ("ear canal" technique; mean values of 8 experiments each).

Relation of sound level to tenderness-toughness. Each of 4 persons chewed 4 samples of tender and 4 samples of tough beef, whose ratings on a 9-point unstructured scale (Raffensperger *et al.*, 1956) were 7.5 and 4.5, respectively. Fig. 8 shows a plot of mean sound level for all 16 determinations for each one of the two foodstuffs (*cf.* Fig. 5, which is based on the same original data).

The mean values for the difference between sound level for tough and for tender meat in the frequency range 800–2500 c/s for the four persons were 1.6, 2.0, 3.2, and 3.5 decibels. Thus, sound level was significantly higher ($p < 0.02$) with tough meat than with tender meat. The combined mean difference was 2.6 decibels, i.e., the intensity of mastication sounds was 35% higher with tough meat than with tender meat.

Time-course experiments. The continuous-tape (nonloop) technique was used to obtain information about the time course of chewing sounds over more extended periods than the 2 seconds covered by the tape-loop technique.

Regularity of chewing. Fig. 9 shows number of bites as a function of time for two experiments with two quite different foodstuffs: crisp brown bread and crisp head lettuce. The common slope of the two lines in Fig. 9 corresponds to a rate of approximately 1.85 bites per second. In other experiments, the values ranged from 1.5 to 1.9 (*cf.* Fig. 11).

General decline in sound level. During normal chewing, the structure of a foodstuff is gradually broken down until the "chew" is ready for swallowing. Such a breakdown can be expected to be paralleled by a decline in the average amplitude of successive bursts of mastication sounds. This factor was studied by chewing various types of food for up to 30 seconds.

Pieces of crisp brown bread, peanuts and half peanuts, small cubes of apple, and pieces of soft white bread were chewed, and the sounds were recorded at a tape speed of 15 inches per second with the microphone pressed to the cheek. During playback at 7½ inches per second, the strip chart was run at a speed of 8 inches per minute. This enabled a measuring of peak amplitudes for the "biting" and "opening" sounds separately while not giving enough resolution to determine the precise shape of the peaks (*cf.* below). Pooled data for biting sounds in three experiments each with three foodstuffs are plotted in Fig. 10. For soft bread, the values usually fell within the region

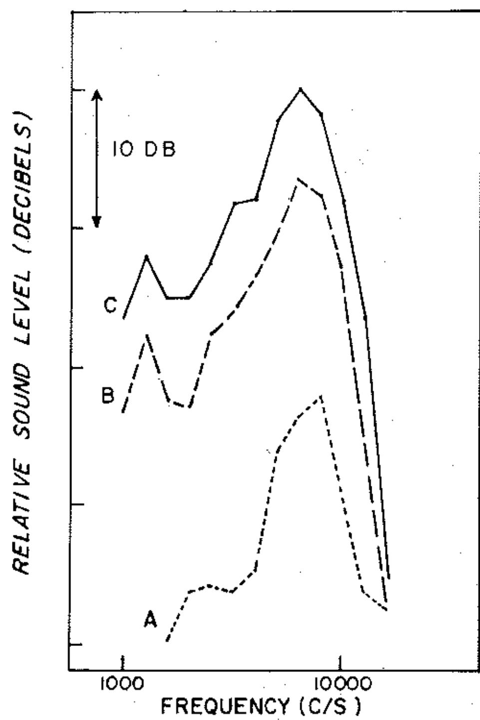

Fig. 6. Sound spectra for soft white bread with various degrees of toasting ("open mouth" technique). A) not toasted, B) light-toasted, and C) hard-toasted.

of general noise, and only a simple calculation of the mean amplitude was performed.

A calculation of regression lines, fitted to the data by the method of least squares, indicated that the first part of the curves for crisp brown bread and for a half peanut could best be represented by the left half of a parabola, whereas a straight line was most appropriate for the apple (*cf.* solid lines in Fig. 10). The actual regression equations were the following (A = amplitude on an arbitrary scale, and t = time in seconds):

Crisp brown bread	$A = 84.5 - 8.78t + 0.33t^2$
Half peanut	$A = 60.1 - 6.54t + 0.256t^2$
Apple	$A = 22.1 - 0.53t$
Soft white bread	$A = 10.6$

The coefficient of the first degree term for crisp brown bread and for half peanuts was significantly different from zero ($p < 0.001$), whereas for apple the coefficient was not significantly different from zero ($p > 0.05$). As determined from these coefficients, the initial average rate of decrease in amplitude was approximately 5.7% per bite for crisp brown bread and for half peanuts.

Fig. 10 shows that a general noise level is reached for various foodstuffs after not more than 15 seconds, corresponding to approximately 20 bites.

Comparison between biting and jaw separation sounds. Some of the tape records used for general decline determinations were re-recorded by the speed-changing playback-procedure described above. The new tape records were then played back without using the electrolytic condenser in the attenuator circuit. This gave strip-chart recordings that were extended enough to permit the plotting of individual curves for sounds produced

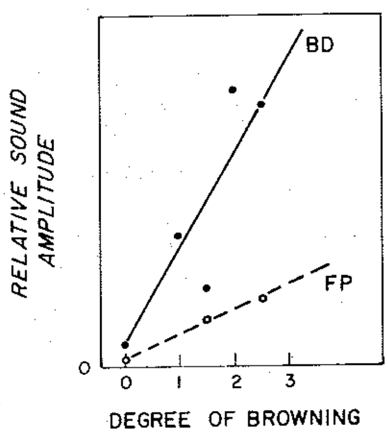

Fig. 7. Relation between degree of browning and peak amplitude of sounds produced by two persons chewing toasts ("open mouth" technique). The scale on the abscissa indicates: 0 = white, 1 = yellow, 2 = brown, and 3 = dark brown.

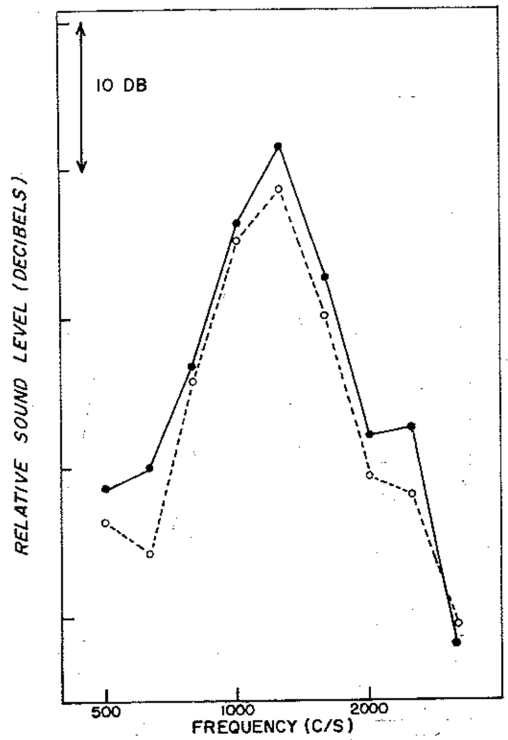

Fig. 8. Sound spectra for 4 persons each chewing 4 samples of tough (●) and 4 samples of tender (○) beef.

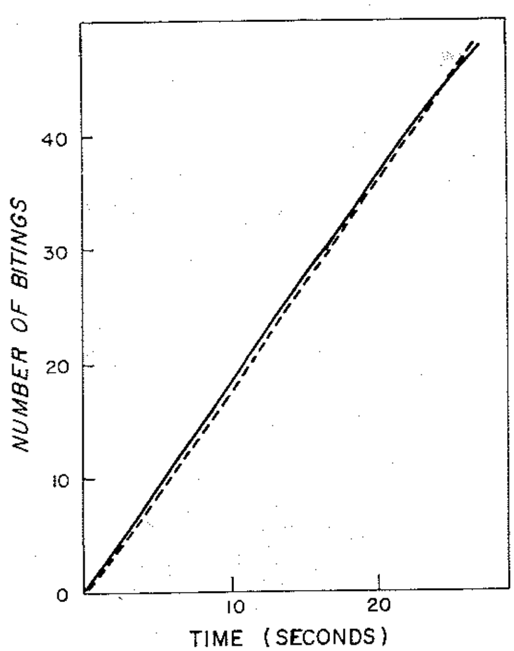

Fig. 9. Number of bites as a function of the time for one person chewing crisp brown bread (----) and crisp head lettuce (——).

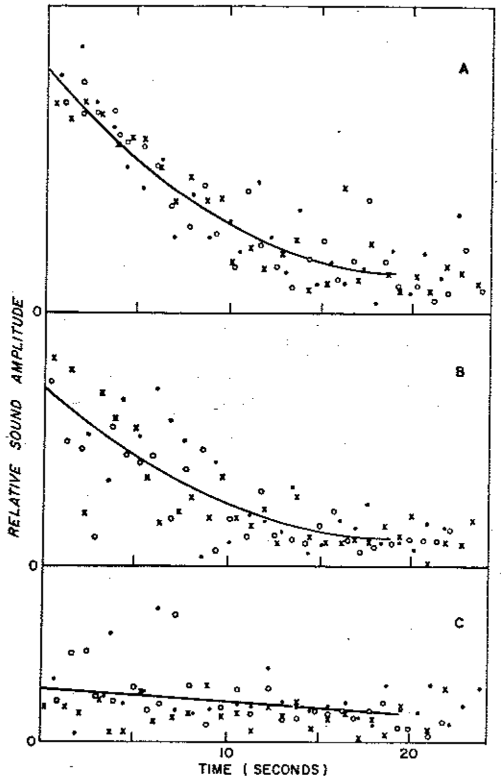

Fig. 10. General decline in mastication sound amplitude for A) crisp brown bread, B) a half peanut, and C) apple. The three types of symbols relate to three different experiments on each foodstuff.

during biting, and for sounds produced during separation of the jaws.

Fig. 11 shows examples of such curves obtained at 50 c/s, which corresponds to an original frequency of 800 c/s, and Fig. 12 shows a visually averaged picture for 12 separate curves.

DISCUSSION

Because of the dampening action of the cheeks and tongue, it can be assumed that practically all vibrations, which are perceived as chewing sounds, reach the inner ear by bone conduction. Thus, the resonance properties of the skull (von Békésy, 1932) tend to equalize the responses for different foods (*cf.* Fig. 3-A). When there is no dampening by soft tissues, however, the differences in crushing sounds between foodstuffs come out larger (*cf.* Fig. 3-B,C).

It can further be assumed that chewing involves a recurrent alternation between a build-up of static forces, when the food is clamped between the teeth, and a burst-out of vibrations, when it is fractured. Thus, it is likely that mastication sounds and related vibrations are utilized as a complement to static clues in subjective estimation of the mechanical properties of food. Such a concept is in accordance with recent work on the dynamic behavior of the sense of touch (Eijkman and Vendrik, 1960), but it would contradict a strict adherence to the opinion that chewing sounds constitute an objectionable noise (Bárány, 1938).

The recording of sounds through the cheek with a commercial microphone probably involves some "seismograph" and/or "accelerometer" action. Thus, this technique may give an empirical measure of differences between foodstuffs, but cannot give easily interpreted information about the actual vibrations of the foodstuffs and of the jaws. The "open mouth" procedure, which can be calibrated by standard methods, does not necessarily give a true picture of normal chewing, in which the vibrations are dampened by contact of the foodstuffs with the soft tissues inside the mouth. The "wood

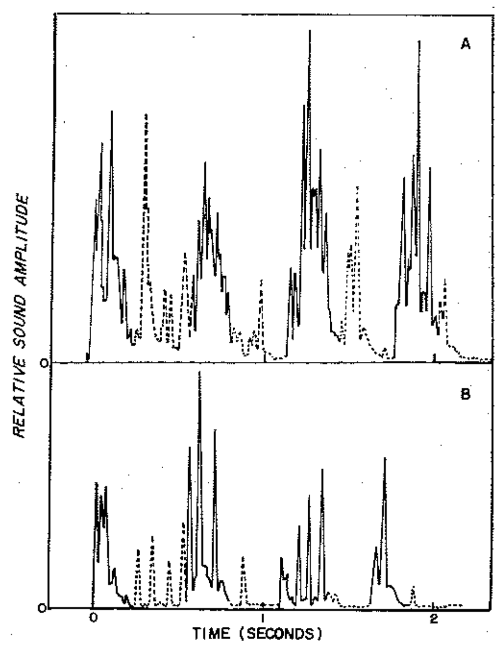

Fig. 11. Mastication sound amplitudes at 800 c/s as a function of time for A) crisp brown bread and B) a half peanut. Solid lines = "biting" sounds; dashed lines = "opening" sounds.

block" and the "open mouth" techniques seem to give similar results, but a final evaluation of the degree of similarity has to await further comparisons. Of course, correlations between the "wood block" technique and other types of rheological measurements would also be useful. The use of an earphone as a pick-up device for airborne sound in the ear canal may give a true picture of bone-conducted sounds, but the possible interference between chewing movements in general and specific food-crushing sounds needs to be explored further before the merits of this method can be established.

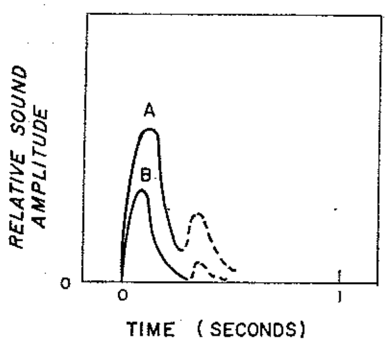

Fig. 12. Visually averaged curves for 12 chews of each of two foodstuffs (for explanations, see Fig. 11).

An introspection showed that the "biting" sounds were produced mainly by the crushing action itself, whereas the "opening" sounds originated both in a reforming of the "chew" and in movements of tongue, teeth, saliva, etc. The "opening" sounds were commonly found for softer foodstuffs in a broad region around 160 c/s (*cf.* Fig. 3-A, ham and sausage). Unfortunately, however, when lower frequencies were reproduced at a very low tape speed, they fell outside the useful range of the equipment, and, consequently, the procedure used to obtain Figs. 11 and 12 could not be used for investigating the time course of such sounds.

One way of increasing the resolving power of the physical analysis described here would be to supplement it with other techniques such as that of "visible speech" (Potter *et al.,* 1947). Unfortunately, such equipment was not available during this exploratory work.

Harrington and Pearson (1962) have found that approximately 25–47 bites are commonly made before pork meat is swallowed. These values are much higher than the highest values at which the mastication sound level decreases to a general noise level (*cf.* Fig. 10 and related text). This suggests the possibility of dividing the normal chewing into two phases, one involving a gross cutting and the other a finer comminution.

Some of the chewing-sound differences between people are appreciable in comparison to the corresponding differences between foodstuffs (*cf.* Figs. 5 and 8), whereas in other cases they are relatively unimportant (*cf.* Figs. 3-B and 4). The data reported here may serve as a starting point for future investigations, which could aim at a careful analysis of, e.g., the statistical variation of sound level within single bites (*cf.* Fig. 11) and other qualitative differences between related foodstuffs, as compared to the mainly quantitative differences reported in Figs. 6 and 8. Also, this type of recording and analysis may prove to be a useful tool in the study of interpersonal differences in chewing behavior. Before chewing-sound data can be utilized in establishing analytical procedures for food testing, however, experiments must be performed and statistically evaluated with many foods and many people. Work in this direction has been planned.

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