Advances in the application of ultrasound in food analysis and processing

Ultrasonic techniques are finding increasing use in the food industry for both the analysis and modification of foods. Low-intensity ultrasound is a non-destructive technique that provides information about physicochemical properties, such as composition, structure, physical state and flow rate. High-intensity ultrasound is used to alter, either physically or chemically, the properties of foods, for example to generate emulsions, disrupt cells, promote chemical reactions, inhibit enzymes, tenderize meat and modify crystallization processes.

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Animals have utilized ultrasound for the characterization and modification of foods for millions of years. Bats and dolphins use low-intensity ultrasonic pulses to determine the size, shape and velocity of the insects and fish that they prey on; while certain marine species use high-intensity pulses of ultrasound to stun their victims before capture. Within the past century, humans have begun using ultrasound to characterize and modify foods, albeit with the aid of sophisticated electronic equipment, rather than natural organs.

Just as in nature, the applications of ultrasound in the food industry can be divided into two distinct categories, depending on whether they use low-intensity or high-intensity ultrasound. Low-intensity ultrasound uses power levels (typically <1 W cm^{-2}) that are so small that the ultrasonic wave causes no physical or chemical alterations in the properties of the material through which the wave passes, that is it is non-destructive. The most common application of low-intensity ultrasound is as an analytical technique for providing information about the physicochemical properties of foods, such as composition, structure, physical state and flow rate[1–3]. In contrast, the power levels used in high-intensity applications are so large (typically in the range 10–1000 W cm^{-2}) that they cause physical disruption of the material to which they are applied, or promote certain chemical reactions (e.g. oxidation). High-intensity ultrasound has been used in research laboratories for many years to generate emulsions, disrupt cells and disperse aggregated materials[4,5]. More recently, a number of novel applications have been developed, including the modification and control of crystallization processes, the inactivation of enzymes, the tenderization of meats, enhanced drying and filtration, and the promotion of oxidation reactions[6–9].

Low-intensity ultrasonic measurements

The three parameters that are measured most frequently in ultrasonic experiments are the ultrasonic velocity, attenuation coefficient and acoustic impedance (Box 1). These parameters are related to the physical properties of foods that are of interest to food scientists, such as composition, structure and physical state.

Ultrasonic velocity

The velocity (c) at which an ultrasonic wave travels through a material depends on its elastic modulus (E) and density (ρ):

$$\frac{1}{c^2} = \frac{\rho}{E} \qquad (1)$$

The modulus used in Eqn 1 depends on whether the material being tested is a gas, liquid or solid, and whether a compression or shear wave is used[10] (Box 1, figure at left). The moduli and densities of materials depend on their structure, composition and physical state; thus, ultrasonic velocity measurements can be used to provide information about these properties.

The ultrasonic velocity of a material can be determined in one of two ways: either the wavelength of ultrasound is measured at a known frequency ($c = \lambda f$), or the time (t) taken for a wave to travel a known distance (d) is measured ($c = d/t$).

Attenuation coefficient

The attenuation coefficient (α) is a measure of the decrease in amplitude of an ultrasonic wave as it travels through a material. The major causes of attenuation are adsorption and scattering. Adsorption is caused by physical mechanisms converting energy stored as ultrasound into heat, for example fluid viscosity, thermal conduction and molecular relaxation. Scattering occurs in heterogeneous materials, such as emulsions, suspensions and foams, when an ultrasonic wave is incident on a discontinuity (e.g. a particle) and is scattered in directions other than that of the incident wave. Unlike in the case of adsorption, the energy is still stored as ultrasound, but it is not detected because its propagation direction and phase have been altered. Measurements of the adsorption and scattering of ultrasound provide valuable information about the physicochemical

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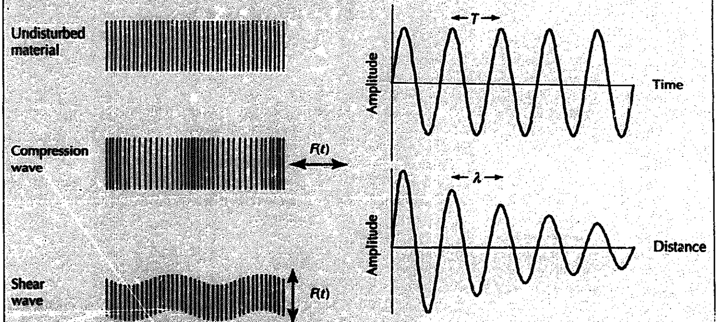
Box 1. The physical principles of ultrasound

Ultrasonic waves are similar to sound waves, but they have frequencies that are too high to be detected by the human ear[9], that is >16 kHz. When an oscillatory force is applied to the surface of a material, it is transmitted through the material because of the bonds between the molecules. If the force is applied perpendicular to the surface, a compression wave is generated, whereas if it is applied parallel to it, a shear wave is generated (see figure at left). In the presence of an ultrasonic wave, the layers oscillate around their equilibrium positions at a frequency equal to that of the ultrasonic wave. When the wave is removed, the layers return to their equilibrium positions; thus, there is no net movement of the layers (except at high intensities).

An ultrasonic wave is characterized by its amplitude (A) and frequency (f), which are chosen by the investigator, and its wavelength (λ) and attenuation coefficient (α), which are fundamental characteristics of a material (see figure at right). The ultrasonic velocity (c) is related to the wavelength and frequency ($c = \lambda f$), and is therefore also a characteristic of a material.



(Left), Ultrasonic waves are generated by the application of a sinusoidal force $F(t)$ to the surface of a material. If the force is applied perpendicular to the surface, a compression wave is generated, but if it is applied parallel to it, a shear wave is generated. (Right), An ultrasonic wave is described in terms of the amplitude of displacement of the layers (shown in the figure at left) from their equilibrium positions. At a fixed position within a material, the displacement varies sinusoidally with time, and the distance between successive maxima is the period (T) (see upper graph). At any instant in time, the amplitude (A) decreases with increasing distance because of attenuation by the sample. The distance between successive maxima is equal to the wavelength (λ).

properties of food materials, including concentration, viscosity, molecular relaxation and microstructure.

The attenuation coefficient of a material can be expressed in nepers per meter (Np m^{-1}) when it is defined by the following equation:

$$A = A_0 e^{-\alpha x} \qquad (2)$$

Here A_0 is the initial amplitude of the wave, and x is the distance traveled. The attenuation coefficient is determined by measuring the dependence of the amplitude of an ultrasonic wave on distance and 'fitting' the measurements to Eqn 2. The attenuation coefficient is often expressed in decibels per meter (dB m^{-1}), where 1 Np = 8.686 dB.

Acoustic impedance

When an ultrasonic wave is incident on an interface between two different materials, it is partly reflected and partly transmitted. The ratio of the amplitude of the reflected wave (A_r) to that of the incident wave (A_i) is called the reflection coefficient (R). For a plane wave that is normally incident upon a plane boundary:

$$R = \frac{A_r}{A_i} = \frac{Z_1 - Z_2}{Z_1 + Z_2} \qquad (3)$$

Here, Z is the acoustic impedance (equivalent to ρc), and the subscripts '1' and '2' refer to the two different materials. Very little ultrasound is reflected from the surface of a material that has a very similar acoustic impedance to its surroundings. In contrast, a high percentage of ultrasound is reflected when two materials have very different acoustic impedances; ultrasonic imaging techniques rely on ultrasound being reflected from internal boundaries between different materials.

Like the ultrasonic velocity and attenuation coefficient, the acoustic impedance is a fundamental physical characteristic, which depends on the composition and microstructure of a material. Measurements of acoustic impedance can therefore be used to provide valuable information about the properties of foods.

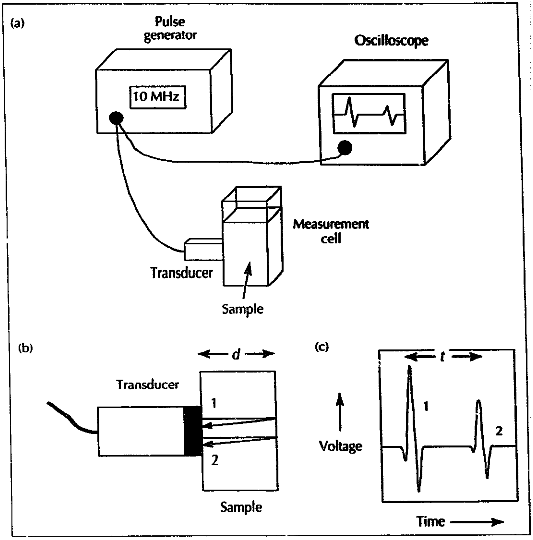


Fig. 1
(a), Schematic diagram of the experimental configuration used to carry out a simple ultrasonic experiment (see text for further details). (b), An ultrasonic pulse travels through a sample and is reflected from the far wall. (c), The pulses are partly reflected and partly transmitted on each reflection, thus a series of echoes is detected (only two are shown). The ultrasonic velocity and attenuation coefficient are determined by measuring the time interval (t) between successive echoes, and their relative amplitudes.

Measurement techniques

One of the major reasons low-intensity ultrasound has not been used more widely in the food industry has been the lack of commercial ultrasonic instrumentation specifically designed to characterize foods. This has meant that researchers have had to design and set up their own experiments, which required a fairly good understanding of the physical principles of ultrasound. This situation is changing, and a number of instrument manufacturers have recently developed ultrasonic devices that are suitable for characterizing foods.

Most ultrasonic instruments utilize either pulsed or continuous-wave ultrasound[9]. Pulse techniques are by far the most widely used because they are easy to operate, measurements are rapid and non-invasive, and the technique can easily be automated. Continuous-wave techniques are used when highly accurate measurements are needed, and tend to be found in specialized research laboratories.

The simplest and most widely used technique for determining ultrasonic measurements is called the pulse-echo technique. A typical experimental configuration consists of a measurement cell containing the sample, a pulse generator, an ultrasonic transducer and an oscilloscope (Fig. 1a). The pulse generator produces an electrical pulse of an appropriate frequency, duration and amplitude. This pulse is converted into an ultrasonic pulse by the transducer, which propagates through the sample until it reaches the far wall of the measurement cell where it is reflected back to the transducer (Fig. 1b). The transducer now acts as a receiver and converts the ultrasonic pulse back into an electrical pulse, which is then displayed on the oscilloscope. Because each pulse is partially transmitted and partially reflected at the cell walls, a series of echoes is observed on the oscilloscope (Fig. 1c). The velocity, attenuation coefficient and acoustic impedance are determined from these echoes. Each echo has traveled a distance twice the cell length (*d*) further than the previous echo, and so the velocity can be calculated by measuring the time interval (*t*) between successive echoes: $c=2d/t$. The attenuation coefficient is determined by measuring the amplitudes of successive echoes: $A=A_ie^{-2\alpha d}$. The acoustic impedance can be determined by measuring the fraction of an ultrasonic wave that is reflected from the surface of a material[9].

It is becoming increasingly popular to measure the frequency dependence of the ultrasonic properties because information can be obtained about the microstructure and molecular dynamics of foods[11,12]. Traditionally, frequency scanning was performed by 'tuning' one or more transducers to a number of different discrete frequencies. Recently, more convenient and rapid methods have been developed that use Fourier transform analysis of broad-band ultrasonic pulses to measure the frequency dependence of the ultrasonic velocity, attenuation coefficient and acoustic impedance[12].

Applications of low-intensity ultrasound

The possibility of using low-intensity ultrasound to characterize foods was first realized over 60 years ago;

however, it is only recently that the full potential of the technique has been realized[1-3]. There are a number of reasons for the current interest in ultrasound.

- The food industry is becoming increasingly aware of the importance of developing new analytical techniques to study complex food materials[10], and to monitor properties of foods during processing[13]; ultrasonic techniques are ideally suited to both of these applications[1-3,14].
- Instruments can be fully automated, can make rapid and precise measurements, are non-destructive and non-invasive, can easily be adapted for on-line applications, and can be used to analyze systems that are optically opaque.
- Rapid advances in microelectronics have led to the development of relatively inexpensive ultrasonic instrumentation that is now commercially available.

The basis of the ultrasonic analysis of foods is the relationship between their measurable ultrasonic properties (velocity, attenuation coefficient and impedance) and their physicochemical properties (composition, structure and physical state). This relationship can either be established empirically by preparing a calibration curve that relates the property of interest to the measured ultrasonic property, or theoretically by using equations that describe the propagation of ultrasound through materials[1-3,11].

During the past 50 years, ultrasound has been used to measure a wide variety of different properties of foods (Table 1). This largely reflects the complexity and diversity of food materials, as well as the versatility of the ultrasonic technique.

Measurement of thickness

Ultrasonic devices are commercially available that can accurately measure the thickness of materials[9]. An ultrasonic transducer is pressed against one side of the material that is to be analyzed, and a pulse of ultrasound is transmitted into the sample. The time (t) this pulse takes to travel through the sample and to be reflected back to the transducer is measured. The distance (d) that the pulse has traveled can be calculated once the velocity of the ultrasound (c) in the material is known: $d=ct/2$.

The advantage of using ultrasound over other methods is that it is necessary to have access only to one side of the material being tested. Thus, it is possible to determine the thickness of materials that are difficult to measure using conventional techniques, such as pipes, chocolate layers on confectionery, fat or lean tissue in meat, liquids in a can and egg shells[1-3].

Detection of extraneous matter

Extraneous matter, such as pieces of metal, glass or wood, often contaminate foods during processing. The presence of these materials in foods is undesirable, and it is therefore important to have analytical methods to detect them. Many foods are optically opaque so that methods based on the transmittance of light cannot be used. In contrast, many foods are acoustically transparent, and are therefore amenable to study by ultrasound. When an ultrasonic pulse is transmitted into a sample, it will be reflected from any surfaces that it encounters (providing that there is a large enough difference in the acoustic impedance of the object and the surrounding material). Materials such as glass, metal and wood have much larger acoustic impedances than most food components and can therefore be detected easily. The presence of an object in a sample can be determined by measuring the time interval between the ultrasonic pulse reflected from it and the pulse reflected from the back wall of the sample container. By moving an ultrasonic transducer around the sample, it is possible to determine both the size and location of the object.

Measurements of flow rate

The rate at which a food material flows through a pipe is important in many food processing operations. A number of ultrasonic devices have been developed that can be used to measure the speed at which a food material flows through a pipe, including Doppler, transit-time and cross-correlation flow meters[2,9]. Ultrasonic flow meters are suitable for determining flow rates of up to a few meters per second on systems ranging from a few millimeters (e.g. the flow of blood in a vein), to greater than a kilometer (e.g. the flow of water in rivers or oceans). Such ultrasonic flow meters measure the average flow velocity across a pipe; however, more sophisticated flow meters have been developed recently that allow measurements of the flow profile across a pipe. It should also be noted that many ultrasonic flow meters actually measure the velocity of the inhomogeneities in a liquid, rather than that of the liquid itself.

Determination of composition

The composition of foods plays an important role in determining their overall quality and cost, and so it is important to have analytical techniques that measure food composition. Ultrasound has great potential for analyzing the composition of foods, and a variety of applications have already been developed (Table 1). The major advantages of ultrasound over other techniques are that it is both non-destructive and rapid, can be used on systems that are optically opaque and can easily be adapted for on-line measurements.

The application of ultrasound for the determination of composition relies on there being a significant change in the ultrasonic properties (e.g. velocity, attenuation or impedance) of a food as its composition varies. The greater the magnitude of the change, the more accurately the composition can be determined. For example, the ultrasonic velocity of a sugar solution increases by ~4 $\mathrm{m\,s^{-1}}$ for each 1% increase in the sugar concentration at 20°C. As it is simple to measure the ultrasonic velocity of a solution to 0.4 $\mathrm{m\,s^{-1}}$, the sugar concentration can be determined to within 0.1%. This technique has been used successfully to determine the sugar concentration of various fruit juices and drinks[15].

Particle size

The size of the particles comprising dispersed systems, such as emulsions, suspensions and foams, often has a pronounced effect on their overall physicochemical properties, for example on their stability, appearance, taste and microbiological status. Consequently, it is useful for food scientists to be able to measure particle size. Conventional methods, such as electron microscopy, light microscopy and laser diffraction, require extensive sample preparation or optically transparent solutions. Ultrasound therefore has important advantages over these techniques because no sample preparation is necessary, and measurements can be made on line.

Ultrasound can be used to determine particle sizes in emulsions or suspensions in a manner that is analogous to light scattering[16]. An ultrasonic wave incident upon an ensemble of particles is scattered by an amount that depends on the size and concentration of the particles. The ultrasonic velocity and attenuation coefficient both depend on the degree of scattering, and can therefore be used to provide information about particle size. In fact, it is possible to determine both the size and concentration of droplets in an emulsion or suspension by measuring the frequency dependence of the ultrasonic velocity and/or attenuation coefficient, and then determining the particle size distribution that gives the best 'fit' between the measured ultrasonic properties and those predicted by theoretical equations that describe the propagation of ultrasound in emulsions[16]. For many emulsions, there is good agreement between theoretical predictions and experimental measurements up to concentrations of 30–40%. By taking ultrasonic measurements over a wide range of frequencies, it is possible to analyze particles as small as 0.02 μm, and as large as a few millimeters. As well as the applications of ultrasound listed in Table 1, there are many other food systems for which ultrasound would be useful for particle sizing; these include mayonnaise, cream liqueurs and margarine.

Table 1. Some examples of the applications of low-intensity ultrasound in the food industry[a]

Application	Food material	Property measured
Composition	Sugar concentration of aqueous solutions	c
	Salt concentration of brine	c
	Triacylglycerols in oils	c, α
	Droplet concentration of emulsions	c, α
	Alcohol content of beverages	c
	Air bubbles in aerated foods	c, α, Z
	Composition of milk	c, α
	Ratio of fat to lean in meats	c, α
	Biopolymer concentration in gels	c, α
Phase transitions	Milk-fat globules	c, α
	Triacylglycerols in fatty foods	c, α
	Water in meat	c, α
Particle size	Oil droplets in salad cream	c, α
	Milk-fat globules	c, α
	Casein micelles	c, α
	Air bubbles in aerated foods	c, α, Z
Miscellaneous	Quality of eggs	c, α
	Ripeness of fruit	c, α, Z
	Texture of biscuits	c, α
	Gelation of gels	c, α
	Cracks in cheese	c, α, Z
	Flow rate of liquids in pipes	t
	Level of liquids in tanks	t
	Detection of extraneous matter	t, Z
	Monitoring enzymatic reactions	c, α
	Molecular interactions of solutes	c, α
	Structure of biopolymers	c, α
	Creaming profiles of emulsion droplets	c, α
	Temperature of foods	t
	Imaging of microbial growth	t, Z

[a] Data taken from Refs 1–3, 10, 13–21

c, Ultrasonic velocity

α, Attenuation coefficient

Z, Acoustic impedance

t, Time for a pulse to travel through the sample and to be reflected back to the transducer

Determination of creaming and sedimentation profiles

An application of ultrasound that is becoming increasingly popular in the food industry is the determination of creaming and sedimentation profiles in emulsions and suspensions. Oils usually have lower densities than water, and so droplets in oil-in-water emulsions move upwards owing to gravity ('creaming'), whereas those in water-in-oil emulsions move downwards ('sedimentation'). The rate at which these processes occur often determines the shelf life of a product. The principle of this application is the measurement of the ultrasonic velocity and/or attenuation coefficient as a function of sample height and time. The ultrasonic parameters are then converted into the physical property of interest (i.e. particle concentration or size), using appropriate mathematical equations. Thus, a detailed analysis of creaming and sedimentation in complex food systems can be monitored non-invasively. This technique can be fully automated, and has the advantage that creaming can be detected before it is visible to the eye. In addition, a detailed creaming profile can be determined rather than a single boundary. This technique should be particularly useful for studying the instability of dairy emulsions, fruit juices, mayonnaises, cream liqueurs and salad creams.

Phase transitions

Many foods contain components that undergo some form of phase transition during manufacture, storage or consumption, for example the melting or crystallization of sugars, oils or water. As the ultrasonic properties of a material change significantly when it melts or crystallizes, ultrasound can be used to monitor phase transitions. One of the most commonly used methods is to measure changes in the ultrasonic velocity with time or temperature. The ultrasonic velocity of solids is significantly greater than that of liquids; thus, the ultrasonic velocity of a sample increases when a component crystallizes, and decreases when it melts. Ultrasonic velocity measurements have been used to monitor crystallization and melting behavior in a variety of bulk and emulsified food fats, including margarine, butter, meat and shortening (Table 1).

Ultrasonic imaging

Ultrasound is routinely used in medicine and materials research to provide images of the internal structure of materials. The same ultrasound techniques can also be applied in food science. Indeed, imaging techniques have already been used to provide information about the ratio of fat and lean tissue, both in live animals and in carcasses. In fact, there are over 100 references to the use of ultrasound for grading animals in the *Food Science and Technology Abstracts* (1969–1995). In contrast to many other applications of ultrasound in the food industry, ultrasonic inspection of meat quality has developed to the stage where commercial instruments are available. Ultrasound imaging would also be useful for monitoring creaming and sedimentation processes in emulsions and suspensions, detecting extraneous matter and measuring crystallization profiles in foods. Ultrasonic imaging instrumentation can now be purchased at relatively low cost (<\$30000), and will almost certainly see greater use in the food industry in the near future.

Advantages and limitations

The main advantages of ultrasound are that it is rapid, precise, non-destructive and non-invasive and can be applied to systems that are concentrated and optically opaque. In addition, it can easily be adapted for on-line measurements, which would prove useful for monitoring food processing operations.

One of the major disadvantages of ultrasonic techniques is that the presence of small gas bubbles in a sample can attenuate ultrasound so much that an ultrasonic wave cannot be propagated through the sample. This problem can sometimes be overcome by taking reflection rather than transmission measurements; however, the signal from the bubbles may obscure those from other components. Another potential problem is that a lot of information about the thermophysical properties (e.g. densities, compressibilities, heat capacities and thermal conductivities) of a material is needed in order to make theoretical predictions of its ultrasonic properties. Theoretical analysis of the data from systems containing many components with unknown properties may therefore be limited. Even so, this should not be a problem if the same system that is being studied is examined routinely. In addition, it is possible to use ultrasound in a purely empirical fashion, by preparing a calibration curve of some measurable ultrasonic parameter versus the physical property of interest.

Applications of high-intensity ultrasound

The principal difference between the applications of high- and low-intensity ultrasound is the power levels used[5]. At low intensities, the power levels are so small that they do not alter the properties of the material through which the ultrasound propagates. At high intensities, an ultrasonic wave generates intense pressure, shear and temperature gradients within a material, which can physically disrupt its structure, or promote certain chemical reactions. The design of the ultrasonic transducers used to generate high-intensity ultrasonic waves is usually very different from that of those used for low-intensity ultrasound applications[5].

There are a large number of potential applications of high-intensity ultrasound in the food industry. Early applications included cell disruption, degassing of liquids, cleaning, homogenization of emulsions and dispersion of aggregated materials[4]. A number of novel applications of high-intensity ultrasound have been developed in the past few years, and some of these are mentioned below.

Promotion of oxidation reactions

Free radicals are generated in water in the presence of high-intensity ultrasonic waves because of the extreme temperatures and pressures produced[6]: $H_2O \rightarrow \cdot H + \cdot OH$. Ultrasound has been observed to promote oxidation reactions in a number of alcoholic beverages, which can be either beneficial or detrimental to their taste[6].

Enzyme inhibition

Prolonged exposure to high-intensity ultrasound has been shown to inhibit the catalytic activity of a number of food enzymes, including pepsin[6]. This is probably because the intense pressures, temperatures and shear forces generated by the ultrasonic waves denature the protein. However, in some cases, solutions containing enzymes have been found to have increased activity following short exposures to ultrasound. This may be due to the ability of ultrasound to break down molecular aggregates, making the enzymes more readily accessible for reaction.

Destruction of microorganisms

High-intensity ultrasound has been used to facilitate the microbial decontamination of various types of food, probably because the high pressures, shear forces and temperatures generated in the material disrupt the integrity of the microorganisms[7]. Ultrasound seems to be particularly effective when used in combination with other decontamination techniques, such as heating, extremes of pH or chlorination[7].

Acoustically assisted diffusion

High-intensity ultrasound can be used to accelerate the diffusion of molecules across membranes and porous materials[8]. This effect has been attributed to acoustic streaming, which is the net movement of fluids in the presence of high-intensity ultrasonic fields. Accelerated diffusion may lead to reduced drying or rehydration times. Ultrasound may also facilitate filtration, ultrafiltration, dialysis and reverse-osmosis processes by continuously 'cleaning' the interface[8].

Modification of meat

Prolonged exposure of meats to high-intensity ultrasonic waves has been shown to lead to significant tenderization[6]. In addition, the application of ultrasound to meat facilitates the release of myofibrillar proteins, which are responsible for binding the pieces of meat together in formed meat products. Thus, ultrasound can lead to improved physical properties of meat products, such as water-binding capacity, tenderness and cohesiveness.

Modification of crystallization

Crystallization can only occur when a material has been supercooled below its melting point. High-intensity ultrasound can be used to decrease the degree of supercooling required to cause nucleation and subsequently crystallization, and also to alter the number and size of crystals formed[6]. These effects may be because small bubbles produced by high-intensity ultrasonic waves act as nuclei, or because fluctuations in the pressure and temperature associated with the ultrasonic wave disturb the equilibrium between solid and liquid phases. By controlling the intensity, duration and frequency of the ultrasonic waves, it may prove possible to modify the size and concentration of the crystals produced. Experiments with concentrated sucrose solutions have shown that the number of small crystals can be increased greatly by subjecting the supercooled solutions to ultrasound[6]. Ultrasonic modification of crystallization processes may prove to be a useful tool for altering the properties of many foods, for example for the modification of the properties of edible fats and spreads, ice creams, chocolates and whipped creams.

Most of the applications of high-intensity ultrasound to foods have been empirical in nature: the food is subjected to ultrasound, and changes in the properties are recorded. More fundamental research is needed to establish the relationship between the duration, intensity and frequency of ultrasonic waves and their effects on the properties of food materials.

Future directions

Applications of both high- and low-intensity ultrasound in the food industry have already been shown to have considerable potential for either modifying or characterizing the properties of foods. In many instances, techniques based on ultrasound have considerable advantages over existing technologies. Low-intensity ultrasound is fairly inexpensive, is capable of rapid and precise measurements, can be used on line or in a laboratory, is non-destructive and can be applied to optically opaque systems. It is surprising therefore that it is not more widely used in the food industry; however, this situation will almost certainly change as new ultrasonic instruments become available, and food scientists become more aware of the potential of the technique. Ultrasound is certainly not applicable to the characterization of every type of food material, but there are many foods for which the technique does have considerable advantages over existing technologies. I believe that the application of ultrasound techniques is most likely to prove fruitful in the near future for monitoring the concentration of aqueous solutions and suspensions, determining droplet size and concentration in emulsions, monitoring crystallization in fats, and monitoring creaming profiles in emulsions and suspensions; in particular, for on-line determination of these properties during processing.

The usefulness of high-intensity ultrasound for modifying certain physical and chemical properties of foods has been realized for many years. Nevertheless, it is only fairly recently that manufacturers have begun to adapt laboratory-scale equipment for large-scale processing operations. The increasing use of high-intensity ultrasound depends largely on the availability of low-cost instrumentation that is proven to have significant advantages over alternative technologies.

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