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Comparison of Ultrasonic Velocities in Dispersive and Nondispersive Food Materials

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Ultrasonic techniques are increasingly being used to evaluate the properties of food materials. Interpretation of the structure and dynamics on the basis of measured ultrasonic parameters requires rigorous definition of ultrasonic parameters such as velocity, especially since many food materials can display considerable dispersive behavior (changes in velocity with frequency). Agar gel (2% w/v) and agar gel (2% w/v) with a regular array of bubbles (8% volume fraction) were chosen as nondispersive and dispersive materials, respectively. Frequency and time domain techniques were used to analyze velocities. Signal, phase, and group velocities were identical in the agar gel and were indistinguishable from those of water (1500 m s^{-1}), indicating the predominant effect of the bulk modulus of the water they contain on the longitudinal modulus of the gel. In contrast, the inclusion of the bubbles in the agar gel led to strongly dispersive behavior, with group velocities varying by 1000 m s^{-1} above and below the 1500 m s^{-1} of the agar gel without bubbles, depending on frequency. The addition of bubbles also led to strong attenuation in the agar gel with a peak occurring at a frequency associated with a band gap arising from destructive interference of sound waves. The results show that care must be taken when comparing ultrasonic parameters derived from experiments on food materials performed at different frequencies or with different ultrasonic techniques.

KEYWORDS: Ultrasound; gel; agar; Fourier analyses; signal analyses; attenuation; bubbles; mechanical spectroscopy; mechanical properties

INTRODUCTION

Low intensity ultrasonic techniques are being increasingly applied to determine a number of technologically useful properties of food materials (*1–4*). One set of properties that has a direct bearing on product stability and acceptability is the food's mechanical (or rheological) properties (*5, 6*). Because these same properties determine how sound waves propagate in materials, we can use information furnished by measurements of ultrasonic velocity and attenuation in food systems to interrogate their structure and evolution of properties with time. By utilizing sound waves covering a range of frequencies, we have the additional advantage of being able to assess the mechanical behavior over a wide range of time and length scales (*7–9*).

A technique typically used to ascertain the ultrasonic velocity in a food material is to measure the propagation of a short ultrasonic pulse through the food specimen (*1, 10*). This pulse is constituted from the superposition of acoustic excitations spanning a continuous range of frequencies, with a width in frequency that is inversely proportional to the pulse length in time. The mechanical oscillations (atomic displacements) that make up the pulse may either be transverse to the direction of propagation (in the case of shear waves) or parallel to the propagation direction (in the case of longitudinal waves). The magnitude of the displacements, ψ, that are evident at a particular time, t, and at a given distance, x, of propagation into the food can be expressed as

$$\psi = \psi_0 \exp i[2\pi(ft - x/\lambda)] \exp[-\alpha(f)x/2] \qquad (1)$$

where ψ_0 is the amplitude of the wave that is actually transmitted into the food material, $\alpha(f)$ is the frequency dependent intensity attenuation coefficient of the food, and f and λ are, respectively, the frequency and the wavelength of the sound. The attenuation coefficient defines how much acoustic energy is lost as the pulse propagates, accounting for the reduction in the magnitude of the pulse that arrives at the detecting transducer. Attenuation is normally a function of frequency, with a frequency dependence that is characteristic of the dissipative mechanism(s) responsible for the acoustic losses. The speed at which oscillations in the wave travel depends on the phase velocity, which is given by $v_p = f\lambda$. Materials that exhibit variation in phase velocity with frequency are referred to as dispersive media, and in such cases,

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it is important to distinguish carefully between the different velocities that describe wave transport (*11, 12*).

A convenient means of expressing both the dissipative characteristics of the food and its ability to transport the strain energy associated with the acoustic disturbance is the wave vector, k (*1, 13*):

$$k = k' + ik'' \tag{2}$$

where the real part of the wave vector, $k' = 2\pi/\lambda$, can be conveniently written in terms of the angular frequency, ω, divided by the phase velocity ($k' = \omega/v_p$), and the imaginary part, k'', is equivalent to half the intensity attenuation coefficient ($k'' = -\alpha/2$). As a result, eq 1 is expressed as follows:

$$\psi = \psi_0 \exp i(\omega t - kx) \tag{3}$$

The wave vector is related to the complex modulus of the food, M, at a specific frequency:

$$\frac{\omega}{k} = \sqrt{\frac{M}{\rho}} \tag{4}$$

where ρ is the food's density. Thus, providing the density is measured independently, measurements of v_p and α for longitudinal waves enable the real and imaginary parts of the wave vector and hence its longitudinal modulus to be obtained, while the corresponding measurements for shear waves permit the shear modulus to be determined (*6*). The real and imaginary parts of these moduli at a variety of ultrasonic frequencies can then be compared with moduli obtained from rheological testing techniques to provide a more complete understanding of the structure and dynamics of the food being investigated (*5, 14, 15*).

To acquire such an overview of food systems in an unambiguous manner, the information generated by ultrasonic experiments should be carefully scrutinized (*6*). For example, substantial variation in velocity values are reported in the literature for ostensibly the same system (*6, 16–19*), and it is not always clear how the measured velocity has been defined. It can be appreciated from eq 1 that the ultrasonic waves that constitute the pulse used to obtain the velocity will be affected by any frequency-dependent absorption that occurs as the pulse propagates within the food. In most classic texts, for example ref *1*, dispersive effects are considered negligible, even though many food materials display considerable dispersive characteristics (*9, 20*). Accordingly, estimates of the moduli derived from eq 4 may vary according to the technique used to measure and analyze the ultrasonic signal, confounding attempts to correctly interpret physical phenomena occurring in the food system.

The objective of this paper was to compare longitudinal ultrasonic velocity and attenuation measurements obtained from both the frequency and time domains and how alternative data processing techniques affect these values. Agar gel was used as a model food system. This choice was predicated on its possession of a network structure that is prevalent in many food systems and and the fact that this structure is homogeneous on length scales larger than 5 μm (*21, 22*), so that dispersion is not expected to be encountered. The addition of 90 ppm (by mass) of air inclusions is then used to demonstrate how readily such well-behaved food systems can display dispersive behavior.

MATERIALS AND METHODS

Agar Gel Preparation. Agar gels of 2% concentration (w/v) were prepared by dissolving granulated agar (Sigma, St. Louis, MO) in distilled water. Each solution was heated over a hot plate in a Pyrex beaker until a temperature of 98 °C was attained. Upon reaching 98 °C, the agar sol was poured into a 12 cm × 12 cm × 6 cm mold to various depths up to 1.5 cm and allowed to cool and gel at room temperature. Samples were also prepared using an alternate procedure in which the hot agar was poured into the mold to a depth of approximately 0.5 cm, the sol was allowed to cool and set at room temperature, and composites of these slabs were then obtained by "gluing" the 0.5-cm-thick slabs together. Up to three 0.5 cm gel slabs were bonded together with a thin layer of liquid agar to create composite specimens. All gels were allowed to set for 12 h at room temperature prior to ultrasonic testing. The thickness of the gel specimens was determined by carefully measuring with a pair of calipers at at least three points across the thickness of the gel. Thickness variation across specimens was of the order of 5%.

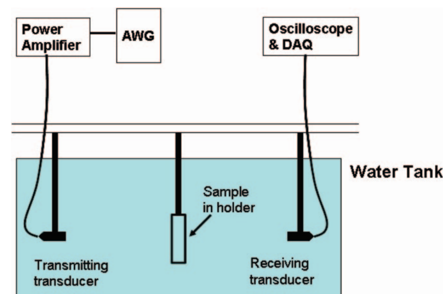

Figure 1. Experimental setup for measuring ultrasonic velocities and attenuation of gel specimens in the frequency domain. AWG represents the arbitrary wave generator, and DAQ represents the data acquisition system.

To prepare 2% agar gels which contained arrays of bubbles, the sol was prepared as above, but then, a very thin layer was first poured into the mold immersed in a waterbath maintained at 60 °C. A second thicker layer of sol was poured after the first layer had cooled, and an ordered triangular array of bubbles in this second layer was created by injecting bubbles into the sol with an eight-array pipette. The mold was removed from the waterbath to gel the sol and retain the bubbles. The process was then repeated to create subsequent layers of gel with bubbles, and finally, a thin layer of gel was added to prevent rupture of bubbles in the top layer. The bubble diameter was 2 mm, and the spacing between bubbles on adjacent layers was 1 mm, creating a multilayer stack with a repeat distance of 3 mm. The layers were arranged such that the bubbles in the second layer were placed over the centres of the triangles formed by the first layer, and the third layer was again displaced relative to the two layers below to create an approximately face-centered-cubic arrangement of bubbles in the gel, with the body diagonal of the cubic cell perpendicular to the layers (*23*). Some variation in bubble diameters and in the final positions occupied by the bubbles once the gel had set led to imperfect ordering of the bubble array.

Ultrasound Experimental Setup. Other than the direct contact measurements, experiments were performed in a large water tank (**Figure 1**). For most measurements, a short voltage pulse (tone burst) containing a couple of oscillations was synthesized by an arbitrary waveform generator (Agilent model 33220A, Agilent Technologies Canada, Mississauga, ON), amplified by a power amplifier (Amplifier Research, model 250L, Souderton, PA), and fed via 50 Ω BNC cables to the generating transducer. The resulting ultrasonic signal traveled through the water, then through the gel specimen, and then water again to the other transducer, which converted the ultrasonic signal into an electronic signal. The detected electronic signal was sent through a variable attenuator to a low noise preamplifier/amplifier combination (Matec model 605, Northborough, MA) and then displayed on an oscilloscope (Tektronix TDS544A, Tektronix Canada, Montréal, PQ). Pairs of broadband immersion transducers (Panametrics, Waltham, MA) with central frequencies of 0.1, 0.25, and 0.5 MHz were used. For direct contact measurements at a given frequency, a gel specimen of a specific thickness was sandwiched between a pair of transducers using a custom-made holder that allowed the distance between transducers to be accurately controlled (*18*).

For experiments in the water tank, the gel specimens were cut to a cylindrical shape, and inserted in a circular hole in an acrylic plate

that was mounted vertically, with the plane of the plate being perpendicular to the horizontal direction of propagation (**Figure 1**). The samples fitted snugly into the hole, which was sufficient to fix the samples in position for the duration of the experiment. The acrylic holder was wrapped with Teflon tape to eliminate transmission of stray sound through the holder. The diameter of the hole was initially 4 cm, but to ensure that passage of the ultrasonic beam would not be obscured by the holder, the diameter was subsequently increased to 6.5 cm and finally to 7.5 cm, for most of the measurements reported here. The test cell containing the gel specimen was mounted on an acrylic holder which was positioned in the water tank with a stainless steel rod. The gel specimen was held in place by screwing the stainless steel rod into a support beam, which also supported the transducers, similarly mounted on acrylic holders screwed into stainless steel rods (**Figure 1**). The distance between transducers was typically around 40 cm, sufficient to ensure that the specimen was placed in the far field of each transducer when positioned equidistant to each. Experiments were performed at room temperature in triplicate.

A reference signal was measured for each set of analyses to enable the propagation time through the specimen and the change in amplitude to be determined relative to the pulse that was incident on the sample. For measurements in the water bath, ultrasonic pulses generated by a given transducer propagated through a pathlength identical to that in which the specimen was situated but consisting of only water at room temperature, i.e., the reference pulse was simply obtained with the specimen removed. For direct contact experiments, the reference pulse was measured by placing the two transducers directly in contact using a very thin layer of ultrasonic coupling gel to ensure good acoustic coupling (*18*).

Analysis of Experimental Results. Values for velocities from time domain analyses were obtained from measurements of the transit time of the ultrasound pulse through the gel specimen and the water reference. To measure phase velocities, group velocities, and attenuation coefficients from the frequency domain analysis, the ultrasonic data were processed using custom software written in C, Matlab, or Igor (Igor Pro, version 6.0, WaveMetrics, Inc., Lake Oswego, OR). Typically, this required truncation of any spurious ringing of the signal after the main pulse and processing of the signals using a fast Fourier transform (FFT) technique (*24*). To determine group velocity as a function of frequency, the reference and transmitted pulses were digitally filtered at selected frequencies using a narrow Gaussian bandwidth that was typically 10% of the central frequency. To ensure good signal to noise ratios and reliable measurements, data are only reported over the frequency range for which the transducer response was greater than approximately 5% of the peak signal amplitude at the central frequency of each transducer.

RESULTS AND DISCUSSION

Time Domain Analyses of Ultrasonic Velocity. In order to accurately measure velocity in a technique such as the pulse-echo or through transmission methods, the time of flight of the acoustic pulse through the specimen must be precisely determined (*1*). Synchronization of the pulse generated by the transducer with that propagated through the specimen is therefore a critical prerequisite, with the instant of the start of the pulse usually marked with a trigger pulse. Ideally, the shapes of the reference and transmitted pulses are identical, so that lining up any given pair of points in the reference and transmitted pulses would furnish identical measurements for the transit time, and thus produce identical determinations of velocity. However, transducer response varies according to the material that it is in contact with, so that a substantially different response is observed for two transducers in contact compared to a transducer in contact with a biological sample. This issue is more of a problem in ultrasonic characterization of biological materials compared to engineering materials because the acoustic impedance mismatch between transducer and biological material is so much greater than between transducer and a material such

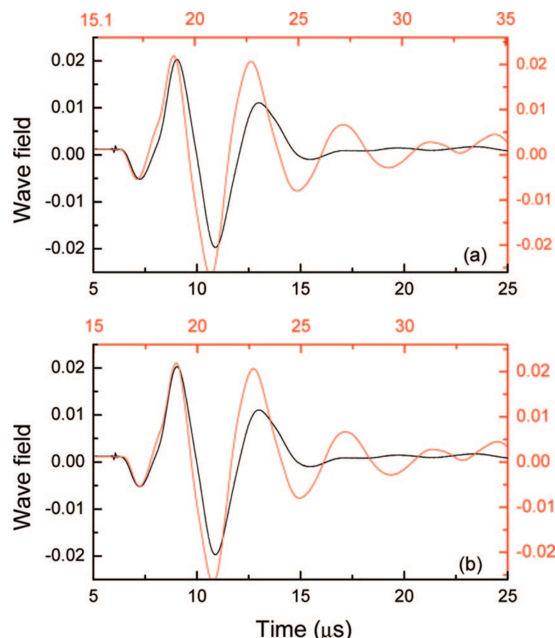

Figure 2. Illustration of how selection of different points in the pulses of reference (black, bottom and left axes) and agar gel specimen (red, top and right axes) leads to differences in measured velocity in direct contact transmission time domain measurements. (**a**) Pulses lined up at their start. (**b**) Pulses lined up at first minimum.

as steel (*10, 12*). Any frequency-dependent effects imposed on this acoustic impedance mismatch can then significantly affect the shape of the waveform and cause transit times determined from different pairs of points in reference and transmitted waveforms to vary. This is illustrated for direct contact measurements of a 2% agar gel (**Figure 2**), where the reference pulse was acquired with the two transducers in direct contact.

In **Figure 2a**, reference and transmitted waveforms are lined up where the signal has clearly started, and a transit time of 10.1 μs is measured, from which a velocity of 1490 ms^{-1} is determined. This point represents the beginning of the main part of the energy associated with the pulse (*10, 11*) and is referred to as the signal velocity. As remarked by Povey (ref *1*, p. 24), the first dip in the waveform is frequently used in commercial instruments for determinations of velocity. This criterion is used in **Figure 2b**, where a slightly shorter transit time is measured (9.98 μs), so that a velocity of 1500 ms^{-1} is derived. Although this difference in velocity is less than 1% for the agar gel, in highly dispersive food materials, the use of single-point determinations of velocity in time domain techniques can lead to significant errors in velocity and hence in assessments of mechanical properties. More robust time domain analyses of velocity can be obtained using multiply reflected signals for materials whose attenuation is low (*20, 25*), and multiple thickness transmission experiments for materials whose attenuation is high (*18*). Again, it is emphasized that these time domain techniques are reliable only when the pulse is not progressively distorted upon multiple reflections within the sample, or as specimen thickness increases.

Frequency Domain Analyses of Phase Velocities. Although the phenomenon of dispersion can thwart accurate measurements of ultrasonic velocity in the time domain, the relaxation events or structural features within the food that give rise to dispersion can provide a more comprehensive definition of the mechanical properties of foods, e.g., characteristic features in frequency-dependent moduli using eq 4 (*5, 9*). To achieve this understanding, frequency domain techniques must be employed and the

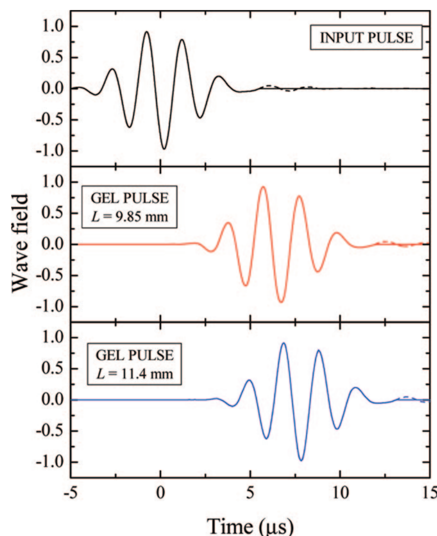

Figure 3. Comparison of the input pulse, determined from the reference pulse through water as described in the text, and pulses that have propagated though 2% agar gel specimens of two thicknesses. Pulses were generated using a 500 kHz broadband transducer. The dotted line represents the signal arising from transducer ringing that was truncated.

phase velocity must be determined as a function of frequency for those frequencies where signal intensity is not obscured by noise (*24*). The phase velocity, which defines how fast a plane of constant phase propagates, was defined above and can be re-expressed as follows:

$$v_p = \frac{\omega}{k} \quad (5)$$

Consequently, if all frequencies within the pulse possess the same velocity, the wave number must increase in step with the frequency, and for this to occur, the cumulative phase must be proportional to frequency.

To evaluate phase velocities in the frequency domain, the data from the reference pulse (which in this case is for a pulse propagating from one transducer to the other through water) and from the pulse having propagated through water and the gel specimen were used to construct a plot of the phase shift against frequency. The first step in achieving this is to determine the input pulse for each reference pulse. Since the attenuation of ultrasound in water is negligible at the frequencies used in these measurements, the input pulse could be determined directly from the reference pulse by shifting the arrival time at the detector by the time taken to travel a distance through water equal to the known sample thickness. For convenience, zero time is set to correspond to the time for the peak of the reference pulse (since only time or phase differences matter). A comparison of the time delay for two thicknesses of the 2% agar gel relative to that of the input pulse is shown in **Figure 3**.

The fast Fourier transform (FFT) of the input and transmitted pulses are then taken, giving the phase and amplitude as a function of frequency. From the difference in phase between the gel specimen and input pulses, the phase shift (or difference), $\Delta\phi$, can then be ascertained:

$$\Delta\phi(\omega) = \phi(\omega) - \phi_0(\omega) \quad (6)$$

where $\phi(\omega)$ is the phase angle at angular frequency ω within the pulse that has passed through the gel and $\phi_0(\omega)$ is the corresponding phase angle in the input signal (**Figure 4**). It can be observed that lines of phase difference for different transducers line up well and that, for both thicknesses, phase differences extrapolate back to zero (as expected, since at zero frequency, i.e., infinite wavelength, there would be no shift in the phase of the wave). Greater phase shifts are apparent at higher frequencies since in a given thickness of gel more wavelengths fit within the thickness of the specimen, and so the phase shift is correspondingly greater. The phase difference increases linearly with frequency since $\Delta\phi(\omega) = \omega t_{prop}$, where t_{prop} is the time taken for a wave at angular frequency ω to travel across the specimen. It is also apparent that there is little or no dispersion of the ultrasound as it propagates through the gel, i.e., the slopes of the lines in **Figure 4** are constant, and so, the phase velocity in 2% agar gel is constant over the hundreds of kHz frequency range.

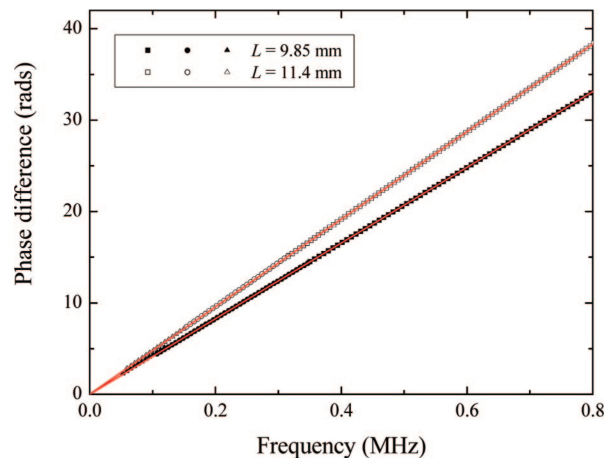

Figure 4. Phase differences versus frequency for specimens of 2% agar gel of 11.4 (open symbols) and 9.85 mm (closed symbols) thickness, measured using transducers having central frequencies of 100 (triangles), 250 (circles), and 500 kHz (squares). Lines represent linear regressions to data.

When attenuation is not large, the phase shift is given by the product of the real part of the wave vector and specimen thickness, L:

$$\Delta\phi(\omega) = k'L \quad (7)$$

From the expression for the phase velocity (eq 5) and eq 7, the phase velocity at selected frequencies can be obtained from the phase shifts of **Figure 4**:

$$v_p(\omega) = \omega L/\Delta\phi(\omega) \quad (8)$$

Phase velocities for 2% agar gel for the frequency range 60–800 kHz are shown as squares in **Figure 5**, and are essentially the same as those in water (*1*), a result expected on the basis of the magnitudes of the shear and bulk moduli of gels. In eq 4, the modulus for longitudinally polarized pulses can be decomposed into contributions from the bulk modulus (B) and the shear modulus (G):

$$M = B + \frac{4}{3}G \quad (9)$$

Since the shear modulus for biological gels can be 10^6–10^9 times smaller than the bulk modulus (*1, 2*), these phase velocities will be dominated by the bulk modulus of the gel (and thus by the incompressibility of the water it contains). These results therefore confirm that detecting gelation by using longitudinally polarized ultrasound is an experimentally challenging task (*26, 27*).

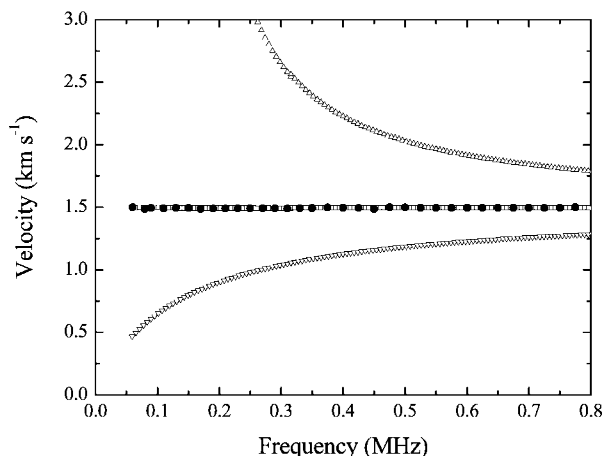

Figure 5. Comparison of the phase velocity (open squares) and group velocity (closed circles) for 2% agar gel determined by Fourier analysis over a wide frequency range. Also shown are incorrect estimates of the phase velocity that would be obtained through erroneous cumulative phase assignments, in which 2π is either added (downward pointing triangles) or subtracted (upward pointing triangles) from the phase shift.

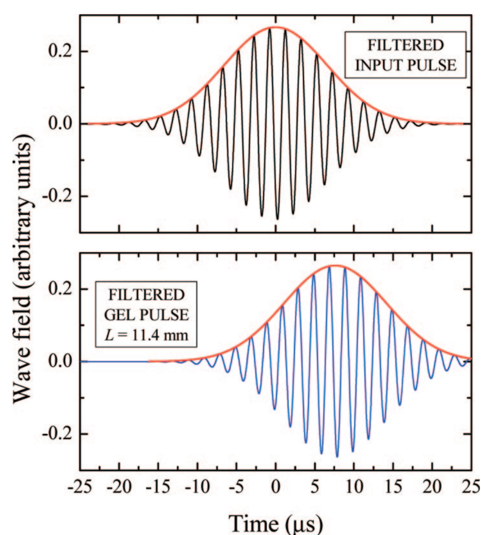

Figure 6. Filtered pulses centred at 0.5 MHz with a 0.05 MHz bandwidth for the input pulse (upper panel) and the transmitted pulse through a 11.4-mm-thick 2% agar gel specimen (lower panel). Solid lines delineating the pulse envelopes are Gaussian fits used for determination of the group velocity.

Frequency Domain Analyses of Group Velocities. A second velocity is needed to describe the propagation of pulses, and this is the group velocity, v_g. This is defined as the velocity at which the peak of the envelope of a pulse centred at a given frequency passes through the gel (*11*), as illustrated for the input and gel pulses in **Figure 6**. Delineation of the envelope is achieved by first rectifying the pulse (taking its absolute value) and then finding the peaks of all oscillations in the pulse to define the envelope (*10, 11*). The group velocity can be expressed as:

$$v_g = \frac{\partial \omega}{\partial k} \quad (10)$$

From a comparison of eqs 5 and 10, one can appreciate that when there is no dispersion, i.e., when the phase velocities do not change with frequency, neither will the group velocities. Conversely, where dispersion does occur, extra information on the food material can be obtained from an evaluation of how the group velocity varies with frequency, since these changes may differ from frequency-dependent changes in the phase velocity (although they are of course related) (*24*).

From the Gaussian filtering technique, group velocities for selected frequencies were obtained across the bandwidth of each transducer (**Figure 5**, shown as solid circles). The filter bandwidth was selected to be 10% of the central frequency of each transducer that was used in **Figures 5** and **6**. This choice of filter bandwidth ensured that pulse shapes were well described by a Gaussian fit (**Figure 6**) and allowed the peak of the pulses to be accurately measured for several frequencies across the bandwidth of each transducer. It can be seen from **Figure 5** that the group velocity is in excellent agreement with the phase velocity across the entire range of frequencies studied and little dispersion of the ultrasound by passage through the agar gel is apparent.

Sensitivity of Velocity Determination to Data Processing. In determining phase and group velocities from frequency domain techniques, there is the scope for introducing errors in data analysis and thus obtaining erroneous values for velocity. Two potential artifacts are discussed: the effect of filter bandwidth on group velocity and the effect of incorrect phase assignment on phase velocity.

Although the choice of filter bandwidth is less critical in a nondispersive medium, bandwidth should be narrow enough that the filtered pulse is Gaussian in the time domain so that the peak of the pulse can be accurately determined. If a very narrow filter bandwidth is selected, the pulse remains Gaussian (the Fourier transform of a Gaussian is also a Gaussian), but the pulse in the time domain becomes very broad because pulse width in the frequency domain is inversely proportional to width in the time domain. For a very broad time-domain pulse, it becomes difficult to accurately determine the peak time of the pulse, and the resulting measurement of the group velocity is less accurate. In addition, there is less averaging of noise across the bandwidth of the pulse, and the velocity measured at adjacent frequencies is scattered. However, in a dispersive medium, a narrow filter bandwidth may be required to limit the range of frequencies in the pulse, so that the filtered time domain pulse is not distorted by pulse spreading arising from waves at different frequencies traveling at different velocities. Limiting the bandwidth in a dispersive medium is essential if the group velocity is to be meaningfully defined for a pulse, and to avoid smearing out the frequency dependence of the group velocity (*24*).

The effect of incorrect phase assignment on values of the phase velocity is shown in **Figure 5**. The open squares represent the phase velocity as a function of frequency determined from the phase shifts in **Figure 4** for the 11.4-mm-thick gel. Incorrect estimates of the velocities in which the cumulative phase difference was mistakenly deemed to be larger or smaller by 2π are denoted by triangles. Determining the correct phase shift is not always straightforward (*24*), particularly at high frequencies, and incorrect assignment (by only one cycle) can be seen to have a substantial effect on velocity determinations. In dispersionless samples, it is easy to determine the correct cumulative phase shift, since this gives a velocity that is independent of frequency and group and phase velocities are equal (so, comparisons of the pulse velocity with the velocity of individual oscillations in the pulse give the same result, and the phase oscillations remain in step with the pulse envelope for any sample thickness). In materials that exhibit large dispersion, it may be necessary to make measurements on samples of different thickness (that are not multiples of each

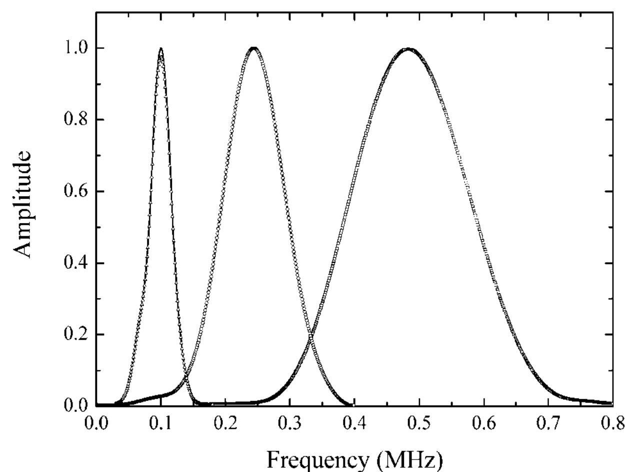

Figure 7. Amplitude spectra for reference signals (solid lines) and transmitted signals after having passed through 9.85 mm of 2% agar gel as determined by three broadband transducers with peak frequencies of 100, 250, and 500 kHz (triangles, upside down triangles, and squares, respectively). For ease of comparison and to clearly show the degree of overlap of the bandwidths of the transducers, amplitudes are normalized so that peaks of the reference spectra are unity.

other) and to follow the phase shift to low frequencies. In the latter case, incorrect phase assignment becomes obvious because the phase shift must extrapolate to zero at zero frequency and errors of 2π in the phase shift are manifest as ridiculously large or small values for the apparent velocities when the frequency is low enough.

Attenuation Coefficient. Typical FFT amplitude spectra for reference signals (solid curves) and signals that have been transmitted through a 2% agar gel specimen (symbols) are shown in **Figure 7**. The entire spectrum between 60 and 700 kHz is covered by the three transducers, although, in the region of 135 kHz, measurements may not be as reliable as this frequency is on the edge of the bandwidth of two transducers. Very little attenuation by the agar gel relative to attenuation of the pulses through water is apparent; indeed, the attenuation is too small to measure accurately without increasing the path length substantially. For the 100 kHz transducer, the amplitude of the pulse through the gel is a little smaller than the reference pulse, but this is a measurement artifact in this case and was not replicated in experiments on other gel specimens.

In general, the frequency-dependent ultrasonic attenuation for a sample can be determined from the ratio of the amplitudes of the transmitted and input pulses using the formula

$$\alpha(\omega) = \frac{2}{L} \ln \frac{A_0}{A} \quad (11)$$

where A_0 is the amplitude of the input signal, A is the amplitude of the signal after it has propagated through the gel, and L is the thickness of the gel specimen. Where there is a difference in the acoustic impedance between the sample and the surrounding medium (water), it is necessary to correct for partial reflection of the incident pulse at the sample interfaces; however, for the agar gel, the mismatch was negligible, and the amplitude of the input pulse is the same as the reference pulse to an excellent approximation. The minor differences between amplitude spectra of the reference and gel indicate that the attenuation coefficient of 2% agar gel over this frequency range is very similar to that of water, which has a value of approximately 0.05 mm^{-1} at room temperature and 1 MHz (*28*). Measurements on 3% agarose gels at 1 MHz using a resonance technique have been reported, and a value of 0.35 m^{-1} has been obtained for the attenuation coefficient (*29*).

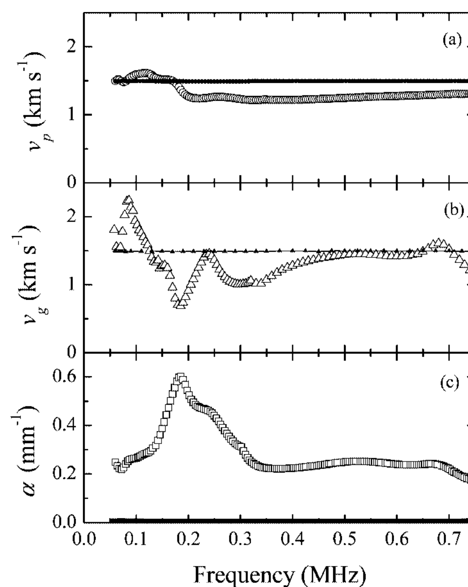

Figure 8. Phase velocity (**a**), group velocity (**b**), and attenuation coefficient (**c**) versus frequency for 2% agar gel containing an ordered array of bubbles of 2 mm diameter (8% volume fraction). The sample has 3 layers of bubbles, with each layer containing approximately 285 bubbles. Gels without bubbles also shown as smaller closed symbols.

Dispersion of Ultrasound in Food Materials. Few food systems are as well behaved as agar gels when probed with ultrasound. Yet, even agar gels can be made to display remarkable dispersive behavior with small amounts of specific inclusions. We can exploit the resulting frequency-dependent changes in the measured ultrasonic parameters to investigate the structure of food materials (*1, 4, 9, 14, 20*). This is illustrated in **Figure 8** for the ultrasonic properties of 2% agar gel to which 90 ppm by mass (but 8% by volume) of air bubbles have been added to the gel.

It can be observed that the frequency dependence of all three ultrasonic parameters, the two velocities and the attenuation, is pronounced and markedly different from the parameters of the pure gel (shown for comparison by the smaller solid symbols). As expected, the variation of the group velocity with frequency is more conspicuous than changes in the phase velocity, and quite strong attenuation is evident across the entire frequency range, accentuated by a peak at approximately 200 kHz. For the large 2-mm-diameter bubbles that were inserted in the gel sample, the main acoustic resonance will occur at much lower frequencies (*4*) and the peak in the attenuation and the associated velocity changes reported here are due not to resonances but to the layered structure of the array of bubbles (see ref *23* and other papers in this special issue of the journal). The main peak in the attenuation occurs at a frequency where half the wavelength is approximately equal to the spacing between layers of bubbles ($\lambda/2 = 3$ mm at $f = 0.25$ MHz in gel), a condition for the formation of a band gap (a range of frequencies where transmission is inhibited by destructive interference) in layered structures with strong acoustic contrast (*30*). While this simple example shows very pronounced effects on the velocities and the attenuation because of the strong scattering contrast between bubbles and the gel (*4*), many food systems have layered structures (*31*), which can also be monitored using ultrasonic techniques, with the potential to determine the thickness of the layers nondestructively.

Conclusions. Agar gel (2% w/w) is a nondispersive material to longitudinally polarized ultrasonic pulses in the 60–800 kHz region. Phase and group velocities and the attenuation coefficient are very similar to those of water, indicating the predominant role of the bulk modulus of water in the gel on ultrasonic properties over this frequency range. Dispersive behavior was readily effected in the agar gel by adding a regular array of bubbles (8% volume fraction) inducing pronounced changes in phase and group velocities over the same frequency range and a peak in the attenuation coefficient at a frequency associated with a band gap arising from destructive interference of sound waves.

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