Änderungen in der Ultraschalldämpfung bei Fleisch während des Gefrierens

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Wir haben früher bewiesen, daß die Ultraschallgeschwindigkeit, die bei Eis größer ist als bei Wasser, angewendet werden kann, um den Prozentsatz von Eis im Gefrierfleisch zu bestimmen. Wir haben jetzt festgestellt, daß die Ultraschalldämpfung, die bisher im Gefrierfleisch nicht gemessen wurde, im Bereich des Ausgangsgefrierpunkts erheblich steigt und im abgetauten Produkt auf einen viel kleineren Wert sinkt. Messungen im Temperaturbereich -20°C bis +40°C bei Frequenzen zwischen 0, 5 und 8 MHz haben erwiesen, daß die Form der Frequenzabhängigkeit des Dämpfungsgrads bei Frisch- und Gefrierfleisch ähnlich ist; der Dämpfungsgrad ist aber beim letzteren höher.

Changes in the attenuation of ultrasound in meat during freezing

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We have shown previously that the velocity of ultrasound, which is greater in ice than it is in water, can be used to estimate the proportion of ice in frozen meat. We now report that the attenuation of ultrasound, which has not previously been measured in frozen meat, increases markedly in the region of the initial freezing point and drops to a much lower value in the unfrozen product. Measurements over the temperature range -20°C to +40°C, at frequencies ranging from 0.5 to 8 MHz, showed that the form of the frequency dependence of the attenuation coefficient was similar in fresh and frozen meat but that the magnitude of the attenuation was higher in the latter.

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Changements de l'atténuation de l'ultrason dans la viande lors de sa congélation

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Nous avons déjà démontré que la vitesse de l'ultrason, laquelle est plus élevée dans la glace que dans l'eau, peut servir à estimer la proportion de glace dans la viande congelée. Nous pouvons maintenant constater que l'atténuation de l'ultrason, qui n'a pas été mesurée avant dans la viande congelée, augmente sensiblement près du point initial de congélation et tombe à un niveau beaucoup plus bas dans le produit non congelé. Des mesures dans la gamme de températures de -20° à +40°C à des fréquences allant de 0, 5 à 8 MHz ont démontré que la forme de la dépendance de fréquence du coefficient d'atténuation a été semblable dans la viande fraîche et la viande congelée, mais que la grandeur de l'atténuation a été plus élevée dans la viande congelée.

Изменение затухания ультразвука в мясе во время замерзания

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Мы уже показали что скорость ультразвука, которая большая во льде чем в воде, может употребляться для оценки доли льда в замороженном мясе. Мы теперь сообщаем, что затухание ультразвука, до сих пор не измеренное в замороженном мясе, значительно увеличивается в зоне начальной точки замерзания и падает до гораздо меньшего значения в незамершем продукте. Измерения в диапазоне температур от -20 до +40°C при частотах от 0,5 до 8,0 МГц показали, что форма зависимости коэффициента затухания от частоты подобная и в свежем и в замороженном мясе, но величина затухания больше в последнем.

Changes in the attenuation of ultrasound in meat during freezing

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Introduction

We have shown previously that the velocity of ultrasound in unfrozen meat changes only slightly with temperature but that at the onset of freezing the velocity increases rapidly so that at -5°C, at which temperature foods such as meat are generally regarded as substantially frozen (Reay, Banks and Cutting, 1950), the velocity has increased by about 70% of its unfrozen value and at -20°C the velocity is roughly double that at 0°C (Miles and Cutting, 1974).

The attenuation of ultrasound has not been measured previously in frozen tissue and in this paper we give a preliminary description of the development of a practical method of measuring it in frozen meat and report how it is affected by the temperature of the product and the frequency of the radiation. We intend to publish a full report elsewhere.

Materials and Methods

Measurements of attenuation Measurements were made using the buffer rod apparatus shown in Fig.1. Discs of piezoelectric ceramic, type PZT5A obtained from Vernitron Ltd., Southampton, U.K., were used to generate ultrasound. Ceramics, resonating (nominally) at 1, 2, 4 and 6 MHz, were mounted centrally on accurately ground hard crown glass cylinders, 5 cm in diameter, using electrically conducting cement as shown in Fig.1. Perspex buffer rods were used at 500 kHz and all rods were made long enough to ensure that the sample was irradiated in the Fraunhofer zone (Wells, 1977) of the ultrasonic beam.

To take measurements a sample was sandwiched between two buffer rods, which were accurately aligned and which carried transducers of the same nominal frequency, mounted in opposition (Fig.1). The temperature was controlled to within ±0.1°C at any level in the range -20°C to +40°C by pumping fluid through a cylindrical enclosure which surrounded the sample and also served to align the buffer rods. The temperature of the sample was monitored with a thermocouple.

Generation and reception of the electrical signals was accomplished using the arrangement shown in Fig.2. A transmitter applied an electrical pulse across one of the ceramics (x) at a repetition frequency of approximately 1 kHz, inducing the emission of short pulses of ultrasound into the buffer rod. When the pulse reached the interface between the buffer rod and the sample part of its energy was reflected, to be returned as an echo to the transmitter, and part was transmitted (Fig.3) to be attenuated in the sample. Further loss occurred when the attenuated pulse was reflected at the second sample/buffer interface and only part was transmitted to be received by the receiving ceramic (Fig.3). This signal was displayed and its amplitude $(Ts)_x$ measured on an oscilloscope together with the first echo $(Rs)_x$ on the transmitter line. The process was repeated using the other ceramic (y) as transmitter which gave transmitted and reflected amplitudes of $(Ts)_y$ and $(Rs)_y$ respectively.

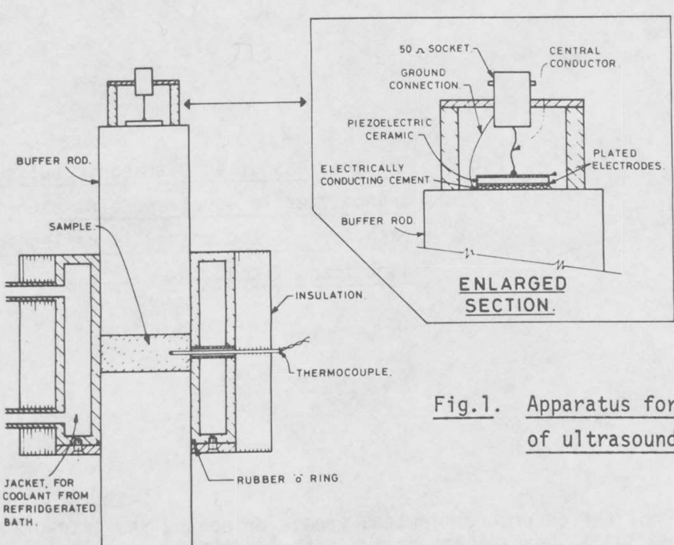

Fig.1. Apparatus for measuring the attenuation of ultrasound in frozen muscle

The whole procedure was repeated with the sample replaced by the same depth (d) of a reference liquid of known properties, either water or ethyl alcohol. This yielded four more values $(Tc)_x$, $(Tc)_y$, $(Rc)_x$ and $(Rc)_y$. These data allowed a comparison between the attenuation coefficients of the sample (α_s), and reference liquid (α_c):

$$\alpha_s = \alpha_c - \frac{1}{2d}\left\{ \ln\left[\frac{(Ts)_x}{(Tc)_x}\;\frac{(1-r_c^2)}{(1+r_x)(1-r_y)}\right] + \ln\left[\frac{(Ts)_y}{(Tc)_y}\;\frac{(1-r_c^2)}{(1+r_y)(1-r_x)}\right]\right\} \qquad (1)$$

$$\text{where } r_x = \frac{(R_s)_x}{(R_c)_x}\,r_c\,,\quad r_y = \frac{(R_s)_y}{(R_c)_y}\,r_c \qquad (2)$$

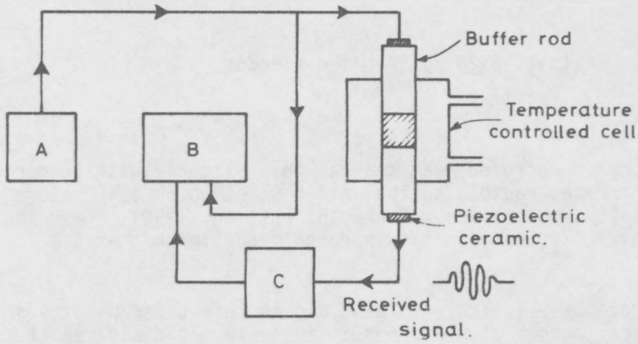

Fig.2. Arrangement for generating and receiving electrical signals

A: transmitter

B: oscilloscope

C: amplifier, if necessary

and $r_c = \dfrac{Z_1 - Z_2}{Z_1 + Z_2}$, where Z_1 = the acoustic impedance or the buffer rod and Z_2 = the acoustic impedance of the reference liquid

Since the attenuation coefficients of water and ethyl alcohol at frequencies up to 8 MHz are much smaller than those of tissue, their contribution in equation (1) is negligible compared with the other terms.

Origin of samples

All muscles were M. semitendinosus dissected from beef sides that had hung for a few days in a chill room at +2°C. Following excision, the muscles were kept at +1°C in polythene bags for a short period until required. In some instances it was necessary to store muscles for a week or more, in which case they were vacuum packaged and stored at +1°C.

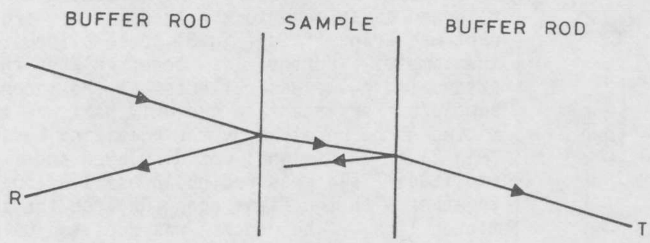

Fig.3. The progress of an ultrasonic pulse from transmitter to receiver. At each interface part of the energy is reflected and part transmitted

Chemical Analysis

200 g of each muscle was trimmed of any external fat cover, comminuted, freeze-dried and the extractable fat content measured by a standard method (Hanson, 1973), Soxhlet extraction with 40° to 60° petroleum spirit.

Effect of temperature

The attenuation in four muscles held at temperatures in the range -20°C to +40°C was measured along the fibres using a Krautkramer USIP10W flaw detector as transmitter (Fig.2) and transducers nominally resonating at 2 MHz. The sample temperature was initially reduced to about -20°C and measurements made after equilibration at this temperature and at set temperatures above.

Effect of frequency

A total of 11 muscles were measured along the fibres at -20°C, 0°C, +20°C and +40°C using transducers nominally resonating at 500 kHz, 1, 2, 4 and 6 MHz. The excitation pulse was derived from a Tektronix FG502 Function Generator, gated to give bursts of radio frequency sine waves at a repetition frequency of about 1 kHz. The radio frequency was set to within ±500 Hz using a counter. Preliminary measurements determined the frequency that gave an optimum response for a given transducer pair and useful readings were also obtained at ±10% of this. Having determined the frequency settings they were kept constant throughout the experiment.

Results

Effect of temperature

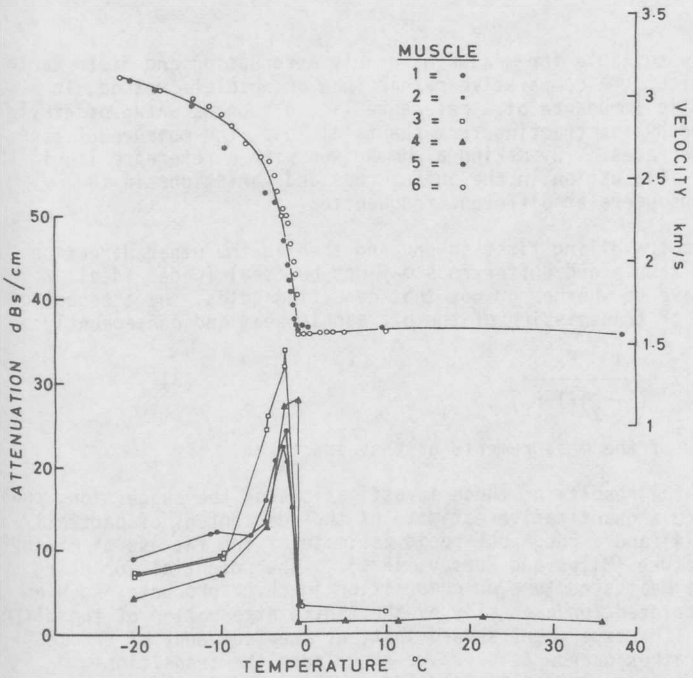

Fig.4. Attenuation and velocity* of propagation of 2.25 MHz ultrasound along the fibres of beef M. semitendinosus

Muscle 1: 1.5% fat , 74.7% water
2: 1.5% fat , 75.2% water
3: 2.2% fat , 74.7% water
4: 1.4% fat , 75.7% water
5: 17.7% fat , 62.3% water
6: 6.8% fat , 70.2% water

* Velocity in comminuted beef at a nominal frequency of 2.5 MHz (data of Miles and Cutting, 1974 and Miles, 1974)

At a centre frequency of 2.25 MHz the attenuation coefficient along the fibres of 4 frozen muscles at -20°C ranged from 4 to 9 dB cm^{-1}. As the temperature was raised the attenuation increased at a rate that increased with increasing temperature until, in the region of -3 to -1°C, each sample showed a marked maximum of between 24 and 35 dB cm^{-1}. From this value the attenuation fell steeply to a relatively low and more slowly varying level in the thawed state: 1 to 3 dB cm^{-1} over the range -0.5 to +37°C (Fig.4).

Table 1. The linear relation between the attenuation coefficient and the frequency of ultrasound transmitted along the fibres of beef M.semitendinosus held at -20°C, 0°C, 20°C and +40°C

Temperature (°C)		Individual Muscles							All muscles pooled
-20	Slope; dB/cm/MHz	3.51 (0.40)	4.39 (0.19)	3.31 (0.17)	4.92 (0.19)				4.05 (0.18)
	Correlation coefficient	0.925	0.989	0.987	0.993				0.952
0	Slope; dB/cm/MHz	1.45 (0.19)	1.83 (0.13)	2.59 (0.12)	2.02 (0.07)	1.44 (0.13)	2.76 (0.28)	1.88 (0.97)	2.01 (0.09)
	Correlation coefficient	0.911	0.973	0.989	0.992	0.948	0.938	0.981	0.918
20	Slope; dB/cm/MHz	1.03 (0.05)	1.37 (0.05)	1.33 (0.07)	1.29 (0.08)				1.25 (0.04)
	Correlation coefficient	0.952	0.991	0.970	0.988				0.971
40	Slope; dB/cm/MHz	2.23 (0.27)	1.99 (0.17)	1.70 (0.18)	1.45 (0.09)	1.71 (0.14)	1.88 (0.09)		1.82 (0.09)
	Correlation coefficient	0.928	0.960	0.952	0.991	0.970	0.988		0.928

Data in brackets are standard errors

Effects of frequency

Graphs showed that the attenuation coefficient increased approximately linearly with frequency over the range 500 kHz to 8 MHz. Least squares linear regression analysis (Table 1) showed that at no temperature did any sample have an intercept significantly different from zero, but there were significant differences between the slopes of individual muscles (Table 1).

Discussion

The method described in this paper is particularly suitable for measuring highly attenuating and distortable substances such as biological tissue, frozen in situ. A comparative rather than an absolute method, it requires a knowledge of the attenuation and acoustic impedance of a reference liquid such as water or ethyl alcohol. Basically the attenuation is calculated by substracting from the total loss, the measured losses caused by the reflections at the glass/sample interfaces. By making a comparison with a reference liquid the technique allows for such affects as beam spread, attenuation in the buffer rods and variations in the sensitivity of the transmitting and receiving transducers at different frequencies.

The expedient of taking measurements with the beam travelling first in one and then in the other direction provides for the fact that the interfaces between sample and buffer rods may not be ideal (under ideal conditions $r_x = r_y$, cf. equation 2). Irrespective of whether or not that condition holds, the attenuation in the sample should be independent of the direction of transmission of the ultrasonic beam and consequently:

$$\frac{(Ts)_x}{(Tc)_x} \frac{(1 - r_c^2)}{(1+r_x)(1-r_y)} = \frac{(Ts)_y}{(Tc)_y} \frac{(1 - r_c^2)}{(1+r_y)(1-r_x)} \qquad (3)$$

Thus equation (3) provides a check on the accuracy of the measurements as they are taken.

It is interesting to consider the implications of the results of these investigations on the suggestions that the velocity of ultrasound might be used to provide a quantitative estimate of the ice content of partially frozen muscle (Miles and Cutting, 1974; Miles, 1974) and a rough but rapid estimate of the fatness of mixtures of fatty tissue and muscle held at a fixed temperature (Miles and Fursey, 1976). The potential for using ultrasound transmission in commerce to interrogate meat structure or composition in thick products, such as commercial blocks of frozen boneless meat, is restricted fundamentally by the finite attenuation of the ultrasonic beam as it propagates through the product. The experiment showed that, at the frequency of the tests, 2.25 MHz, the attenuation in muscle peaks over a rather narrow temperature range near the transition temperature (Fig.4). It follows that meat undergoing a process of freezing or thawing will attenuate an ultrasonic beam substantially whenever there exists within it a substantial region of frozen tissue near the transition temperature. This property itself might be useful in monitoring progress in freezing and thawing. The actual attenuation of a partially frozen block can be computed from the results of Fig.4 if the temperature distribution within the block is known and the choice of an appropriate frequency for measuring pulse transit times will rest on balancing the benefits of increased resolution at high frequencies against the increase in attenuation (Table 1) and consequent reduction in the depth of tissue that the ultrasonic beam will penetrate.

In attempting to use measurements of the velocity of ultrasound transmission to estimate the fatness of frozen mixtures of muscle and fatty tissue, the results of this investigation indicate that there will be a considerable advantage in reducing the temperature of the product to as low a temperature as possible. The results have shown that at -20°C, for example, lean meat is considerably more transparent to ultrasound than it is at -10°C. The question of whether or not attenuation in the fat will significantly affect the issue awaits measurements of the attenuation in fatty tissue.

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