

# Measurements of acoustic properties of aqueous dextran solutions in the VHF/UHF range

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## Abstract

The acoustic properties of aqueous solutions of dextran are characterized in the frequency range of 70–400 MHz by the bio-ultrasonic spectroscopy system using an ultrasonic transmission comparison method. The attenuation, velocity, impedance, and density of aqueous dextran solutions, for six molecular weights in the range of 10,400–2,000,000 Da in the concentration range 5–20% by weight, are reported. All four parameters increase with increasing concentration. As the molecular weight increases, the attenuation coefficient increases and the velocity decreases. The precise frequency and molecular weight dependences of the acoustic properties of the solutions are readily determined by the system. © 2000 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Studies on biological tissue characterization using ultrasound have been conducted for more than half a century [1]. The bioultrasonic spectroscopy system was developed for biological tissue characterization in the VHF/UHF range in order to investigate the acoustic properties of tissues and liquids [2], and has been applied to studies of bovine tissues and biomacromolecular liquids such as bovine hemoglobin solutions, and egg yolk and albumen in the VHF/UHF range [3,4]. The bioultrasonic spectroscopy system determines the attenuation coefficient, velocity, impedance, and density with a high accuracy by an ultrasonic transmission comparison method, using pure water as the reference.

Biological soft tissues are composed of water and a variety of biomacromolecules, such as proteins and lipids, of which acoustic properties need to be available and understood in order that the acoustic properties of tissues can contribute to biology and to medicine.

Fundamental studies of these acoustic properties have been mainly conducted at the frequencies below 10 MHz, and the relations between the properties and their constituents have been discussed [1]. Dextran, a linear carbohydrate, is available commercially in a series of molecular weights, and in aqueous solution it is convenient for studying the relation between acoustic properties and molecular weight. Studies of the acoustic properties of aqueous solutions of dextran and sugars have been conducted by Hawley and Dunn in the lower frequency range [5] and by Gracewski et al. in the UHF range [6]. Because of the increased interest in ultrasonic studies in the VHF/UHF range, due to the developments of acoustic microscopy, it is felt that increased accuracy is required in the molecular weight dependence of the acoustic properties of dextran aqueous solutions.

In this paper, the acoustic properties of aqueous solutions of dextran are characterized in the frequency range of 70–400 MHz by the bioultrasonic spectroscopy system. The attenuation, velocity, impedance, and density of the solutions, for six molecular weights of dextran from 10,400 to 2,000,000 Da in the concentration range of 5–20% by weight, have been measured and are reported as a function of frequency, concentration, and molecular weight.

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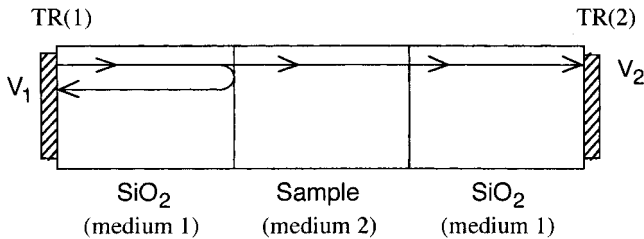


Fig. 1. Definition of transducer outputs  $V_i$  for measuring acoustic properties of liquid samples.

## 2. Measurement method

The measurement method and system is described in detail elsewhere [2], but is briefly noted herein. The experimental configuration is shown in Fig. 1, in which a specimen is inserted between the parallel surfaces of synthetic silica ( $\text{SiO}_2$ ) buffer rods having ZnO piezoelectric film transducers on their outer ends. An RF burst signal is applied to the transmitting transducer TR(1) in order to generate ultrasonic longitudinal plane waves, which then propagate in the buffer rod. The ultrasonic attenuation coefficient, velocity, impedance, and density are determined from measurements of the transducer outputs  $V_i$  ( $i = 1, 2$ ), considering the buffer rods and sample as an ultrasonic transmission line model.

In the measurement method, the acoustic properties of water and  $\text{SiO}_2$  are used as the references. The velocity of water reported in the literature [7], and the measured attenuation coefficient of water and the acoustic impedance of  $\text{SiO}_2$  were employed as the reference data. The values of the attenuation coefficient  $\alpha$  divided by the square of frequency  $f$  for water and the impedance for  $\text{SiO}_2$  were  $\alpha/f^2 = 2.23 \times 10^{-14} \text{ s}^2/\text{m}$  and  $13.11 \times 10^6 \text{ N s/m}^3$  at  $23^\circ\text{C}$ , respectively.

In velocity measurements, the  $z$ -interference method [2], in which the frequency is fixed and the ultrasonic propagation distance is varied, is used. The attenuation coefficients and velocities are measured in the transmission mode using the transducer output  $V_2$ . The acoustic impedances are measured in the reflection mode using  $V_1$ . The density  $\rho$  is calculated by using the equation that  $\rho = Z/v$ , where  $Z$  is the acoustic impedance and  $v$  is the velocity.

## 3. Experiments and results

The ultrasonic devices for measurements consist of ZnO piezoelectric film transducers fabricated on one end surface of each of the  $\text{SiO}_2$  buffer rods. The devices have an operating center frequency of 420 MHz. The diameter of the transducer is 1.3 mm. The buffer rods are

8 mm long and have a diameter of 8 and 20 mm for the transmitter and receiver, respectively.

The measurement accuracy in the present study is estimated to be better than  $\pm 0.1\%$  for velocity and  $\pm 1\%$  for attenuation coefficient, impedance, and density. The reproducibility is estimated to be better than  $\pm 0.02\%$  for velocity and  $\pm 0.5\%$  for the attenuation coefficient, impedance, and density.

Aqueous solutions, prepared with dextran (Sigma Chemical Co.) and pure water, were stirred at room temperature and degassed under vacuum. The concentrations of the solutions were 5%, 10%, 15%, and 20% by weight. The molecular weights of the six dextran samples were 10,400, 19,500, 42,000, 167,000, 460,500, and 2,000,000 Da.

The measured attenuation coefficients of the aqueous dextran solutions in the frequency range of 70–400 MHz at  $22.9$ – $23.3^\circ\text{C}$  are shown in Fig. 2. The lower line in the figure is the attenuation coefficient of water at  $23^\circ\text{C}$ , which is proportional to the square of the frequency, and measured by the bioultrasonic spectroscopy system. The attenuation curves in each concentration group are close to one another. Fig. 3 shows the attenuation coefficients at 200 MHz as a function of the molecular weight of each dextran sample. Above the concentration of about 10%, the attenuation coefficient increases as the molecular weight increases. This molecular weight dependence of attenuation also occurs at the other frequencies.

The attenuation coefficients of the aqueous solutions of dextran are greater than that of the solvent water. The attenuation coefficients of the solutions, which have

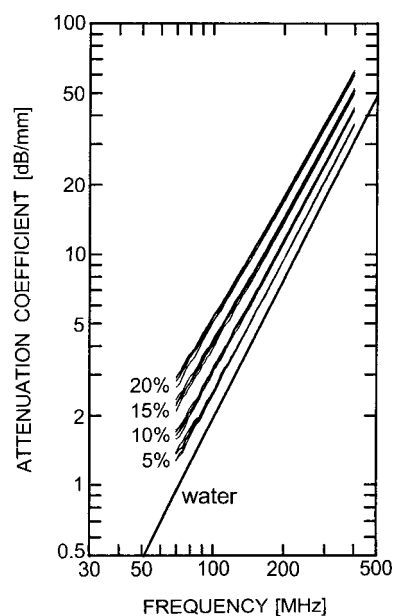


Fig. 2. Frequency dependence of attenuation coefficients of aqueous dextran solutions at  $22.9$ – $23.3^\circ\text{C}$ .

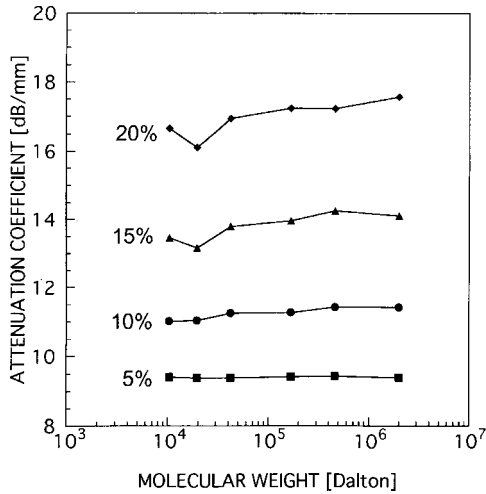


Fig. 3. Molecular weight dependence of attenuation coefficients of aqueous dextran solutions at 200 MHz.

the same concentration but different molecular weights, have nearly the same magnitude and frequency dependences. The attenuation coefficients for the 5% and 20% concentrations are proportional to the 1.85 and 1.70 power of frequency around 70 MHz and gradually increase with frequency up to the 1.95 and 1.85 power around 400 MHz, respectively (Fig. 2). It is suggested that the frequency dependence of the attenuation coefficients approaches the frequency squared dependence as the frequency continues to increase beyond 500 MHz.

Fig. 4 shows the measured velocities of aqueous solutions of dextran at 200 MHz as a function of molecular weight at 23.0–23.3°C.

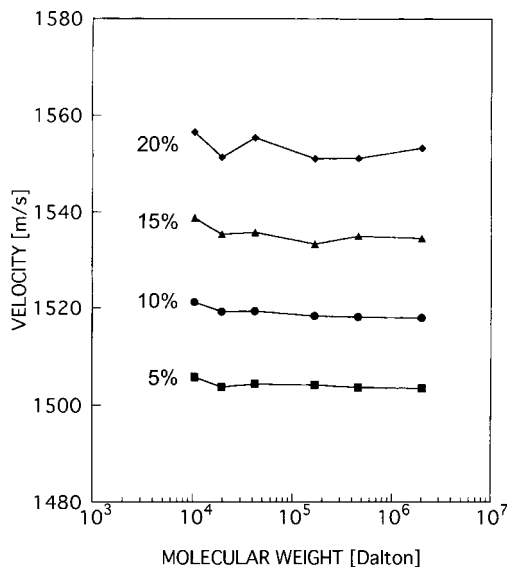


Fig. 4. Molecular weight dependence of velocities of aqueous dextran solutions at 200 MHz at 23.0–23.3°C.

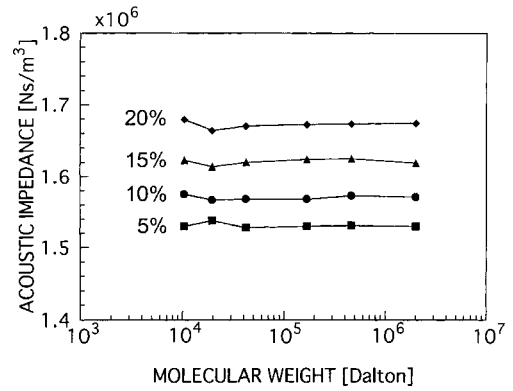


Fig. 5. Molecular weight dependence of acoustic impedances of aqueous dextran solutions at 150–400 MHz at 22.9–23.3°C.

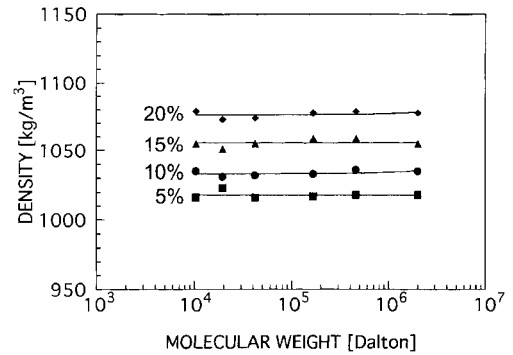


Fig. 6. Molecular weight dependence of densities of aqueous dextran solutions.

Fig. 5 shows the measured acoustic impedances of aqueous solutions of dextran at 22.9–23.3°C. These acoustic impedance values are the averaged values in the frequency range 150–400 MHz, in which a frequency dependence of the acoustic impedances is not observed.

Fig. 6 shows the density determined from the measured velocities and acoustic impedances. The deviations of densities from the average values among the six molecular weights of dextran are within  $\pm 0.5\%$ , which is the same as the reproducibility of the measurements. The averaged densities for the six molecular weights are 1018, 1034, 1056, and 1077  $\text{kg/m}^3$  for the concentration of 5%, 10%, 15%, and 20%, respectively.

#### 4. Discussion

##### 4.1. Concentration dependence

Fig. 7 shows the attenuation coefficients of aqueous solutions of 10,400 Da dextran as a function of concentration at 200 MHz. The closed circle at 0% is the measured attenuation coefficient of water at 23°C. The

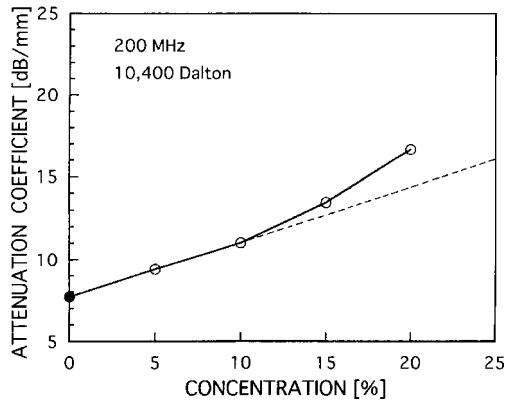


Fig. 7. Concentration dependence of attenuation coefficients of aqueous dextran solutions at 200 MHz.

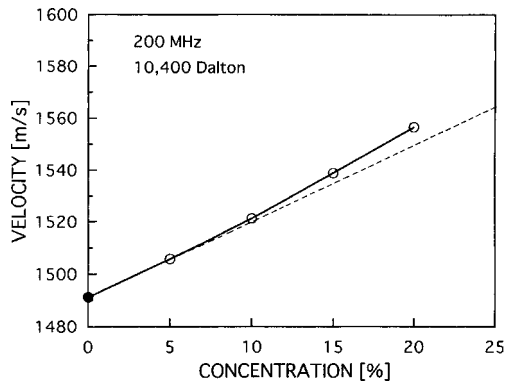


Fig. 8. Concentration dependence of velocities of aqueous dextran solutions at 200 MHz.

solid line connects the attenuation values and the dashed line connects only the values for 0% and 5%. Below about a concentration of 10%, the ratio of the attenuation variation  $\Delta\alpha$  to the concentration variation  $\Delta c$ ,  $\Delta\alpha/\Delta c$ , is really constant. Above 10%, the ratio  $\Delta\alpha/\Delta c$  increases as the concentration increases.

Fig. 8 shows the velocities of the dextran solutions as a function of concentration at 200 MHz. The closed circle at the concentration of 0% is the velocity of water [7] at the measurement temperature. The solid and dashed lines represent the same purpose as in the case of attenuation. On the whole, the ratio  $\Delta v/\Delta c$ , the velocity variation  $\Delta v$  to the concentration variation  $\Delta c$ , increases as the concentration increases.

Figs. 9 and 10 show the acoustic impedance and density of aqueous solutions of 10,400 Da dextran as a function of concentration, respectively. The closed circles in Figs. 10 and 9 at the concentration of 0% are the density [8] and impedance, obtained by calculating the product of the velocity and density, of water at the measurement temperature. As the concentration increases, the acoustic impedance increases monotonically and the density increases linearly.

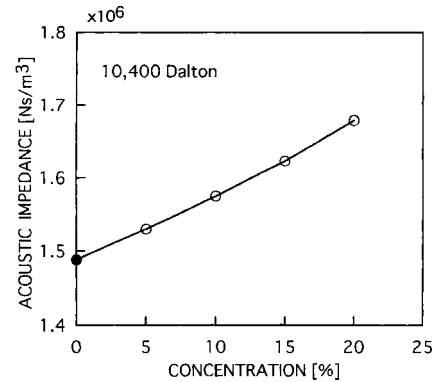


Fig. 9. Concentration dependence of acoustic impedances of aqueous dextran solutions.

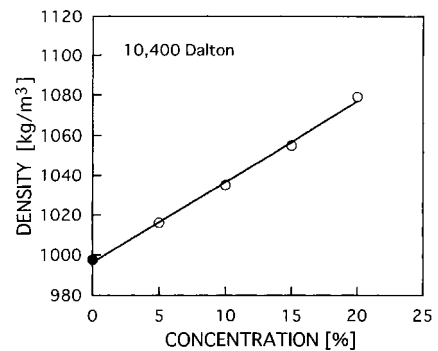


Fig. 10. Concentration dependence of densities of aqueous dextran solutions.

#### 4.2. Molecular weight dependence

Fig. 3 shows the attenuation coefficients of aqueous solutions of dextran at 200 MHz as a function of molecular weight. The attenuation values for the concentration of 5% are really constant with respect to molecular weight. Above about 10%, the attenuation increases as the molecular weight increases. As the concentration increases, the ratio of the attenuation variation to the molecular weight variation increases. This molecular weight dependence of the attenuation is observed at the other frequencies also.

The absorption coefficients of aqueous solutions of dextran and sugars were measured as a function of molecular weight by Hawley and Dunn [5] and by Gracewski et al. [6]. Hawley and Dunn [5] reported the absorption of aqueous solutions of dextran in the molecular weight range of 3400–370,000 Da in the frequency range of 3–51 MHz below the concentration of 10% that the absorption is constant above the molecular weights of 25,000 Da. Gracewski et al. [6] measured the absorption coefficients of aqueous solutions of sugars in the molecular weight range 5000–2,000,000 Da at 1 GHz at the concentration of 5%; the molecular weight dependence was not observed also. The measurement fre-

quency range 70–400 MHz, in this report, is not the same as the two previous reports, though the molecular dependence of the attenuation coefficients observed in this paper, at the concentration of 10%, may be the first such report.

Fig. 4 shows the velocities at 200 MHz as a function of molecular weight, showing that as the molecular weight increases, the velocities decrease for all concentrations.

## 5. Summary

In this paper, aqueous solutions of dextran have been characterized in the frequency range of 70–400 MHz by the bioultrasonic spectroscopy system. The attenuation coefficient, velocity, acoustic impedance, and density have been measured for the solutions in the dextran molecular weight range of 10,400–2,000,000 Da for the concentrations 5%, 10%, 15%, and 20%.

All the acoustic parameters increase monotonically with concentration. It is noted that as molecular weight increases, attenuation increases but velocity decreases.

The bioultrasonic spectroscopy system can obtain frequency dependence and molecular weight dependence

of the acoustic properties of the solutions, which could not be accomplished by earlier methods.

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