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Experimental measurement of the acousto-electric interaction signal in saline solution

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Abstract

Acoustic pressure alters local electrical conductivity in tissues and solutions. This work concerns the measurement of electrical conductivity in a liquid which is subjected to an acoustic pressure field created by a focused transducer. Measurements were made with four electrodes positioned in the ultrasonic focal zone, and the signal concerned is referred to as the acousto-electric interaction signal. A solution of sodium chloride in a measurement cell was subjected to ultrasound pressures of upto 1 MPa. It was shown that it is possible to quantitate the acousto-electric interaction signal once the ultrasonic vibration potential due to the Debye effect has been subtracted. The acousto-electric interaction signal was shown to be directly proportional to both the applied acoustic pressure and current. For the measurement cell used in this work, the interaction factor was found to be 5.3 $\mu V\, mA^{-1}\, MPa^{-1}$. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The effects of high-intensity therapeutic ultrasound on biological media, particularly cavitation and thermal effects, have been widely investigated. However, other effects can also be produced by relatively low-intensity ultrasound.

A variety of biological effects have been discussed in the literature. Ultrasound is known to produce irreversible cell damage [1,2]. Ultrasound can promote the healing of soft tissue [3] and bone repair [4] and can be used to stimulate nerve cells [5]. Ultrasound can induce a wide range of physical effects such as platelet aggregation [6], or platelet orientation [7]. Ultrasound also mediates subtle effects on conductive media through adiabatic compression effects: both pressure and temperature affect the electrical conductivity of electrolytes [8,9].

The propagation of an acoustic wave induces local changes in conductivity so that a current passing through an electrolyte can be modulated by an acoustic field; this effect is referred to as the acousto-electrical interaction (AEI) signal. This field has not been extensively investigated and is only touched upon in a handful of papers. In a direct application of this effect, making pressure measurements using a cell containing a conducting electrolyte solution has been proposed [10]. Certain authors have speculated that this effect might be exploited to stimulate the brain in a highly localized fashion [11,12].

There are several difficulties associated with measuring the AEI signal. The first difficulty results from the fact that only a very small change in conductivity is induced by a change in pressure (e.g. 0.1% per MPa for NaCl solution); therefore, the AEI signal has a very low amplitude. The second problem is a consequence of one of the other effects of ultrasound, the ultrasonic vibrational potential (UVP) or Debye effect [13–15]. Without any current being applied, acoustic pressure changes induce a potential difference, the amplitude of which is also a function of pressure. Thus, the AEI signal readings can be distorted by Debye potential differences.

As ultrasound-induced potential differences and all the associated phenomena are discussed in a previous

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work [16], this article concerns the actual experimental measurement, in sodium chloride solution, of AEI signals associated with ultrasound-induced changes in conductivity. The relationship of the AEI signal to the applied current and pressure was investigated.

2. Principle

A uniform conducting medium with a conductivity σ_0 contains two electrodes of area S, separated by a distance l (Fig. 1). These electrodes are used to pass a constant current i through the medium. Assuming that the paths of the current are parallel to the axis formed by the electrodes, the voltage v at the electrode terminals is given by

$$v = i\frac{1}{\sigma_0}\frac{l}{S} = R_0 i, \tag{1}$$

where

$$R_0 = \frac{1}{\sigma_0}\frac{l}{S} \tag{2}$$

and R_0 is the resistance experienced by the electrodes.

The application of an ultrasound field induces a pressure variation dp which causes a change in conductivity given by

$$\sigma = \sigma_0 + \mathrm{d}\sigma. \tag{3}$$

In consequence, there is a voltage change dv given by

$$\mathrm{d}v = -i\frac{\mathrm{d}\sigma}{\sigma_0^2}\frac{l}{S}. \tag{4}$$

Since the change in conductivity is proportional to the change in pressure [16], Eq. 4 can be rewritten as

$$\mathrm{d}v = kiR_0\,\mathrm{d}p. \tag{5}$$

As shown by Eq. 5, any ultrasound-induced change in conductivity gives rise to a change in voltage, i.e. the AEI signal, which is proportional to both the magnitude of the pressure change and the amount of current flowing through the medium.

If the pressure change dp is of the form

$$\mathrm{d}p = \mathrm{d}p_0 \cos\omega t, \tag{6}$$

a voltage dv will be generated at the same frequency as the pressure signal.

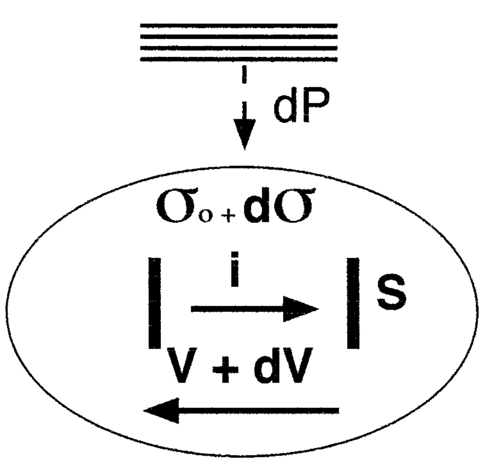

Fig. 1. Principle of acousto-electric interaction.

3. Materials

3.1. Experimental set-up

To detect changes in electrical conductivity induced by changes in acoustic pressure, the experimental set-up shown in Fig. 2 was used. A measurement cell containing electrodes and a conducting solution was immersed in a large, rectangular tank with internal dimensions of 23 cm (width) × 30 cm (height) × 52 cm (length) filled with degassed water. A focused transducer was mounted on one of the smallest sides of this tank. An absorbing surface was mounted opposite the transducer to prevent standing waves. All measurements were made at room temperature 20 ± 2°C.

3.2. Ultrasound generator

All measurements were made using a 500 kHz transducer, 50 mm in diameter and focused at 165 mm. A quarter wave plate was used for acoustic matching and the transducer impedance was electrically matched to 50 Ω by a transformer. The transducer drive power was pulsed in order to generate high acoustic pressure levels without overheating the solution and running the risk of cavitation. This supply wasgenerated by a function generator (Hewlett Packard type 8116) operating in burst mode. The power driving the emission of ultrasound waves comprised 10 sinusoidal periods at a frequency of 500 kHz. The recurrence frequency for the bursts was 100 Hz. This function generator was connected to an amplifier (KALMUS type 150C). This set-

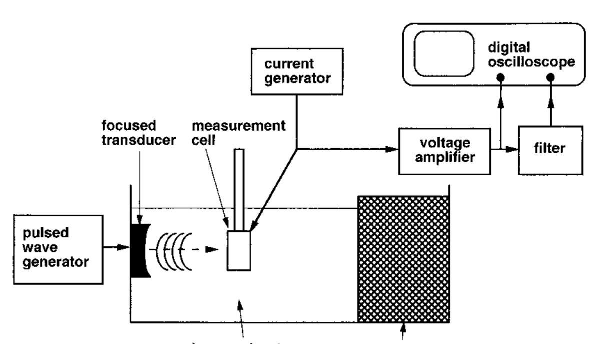

Fig. 2. The experimental set-up.

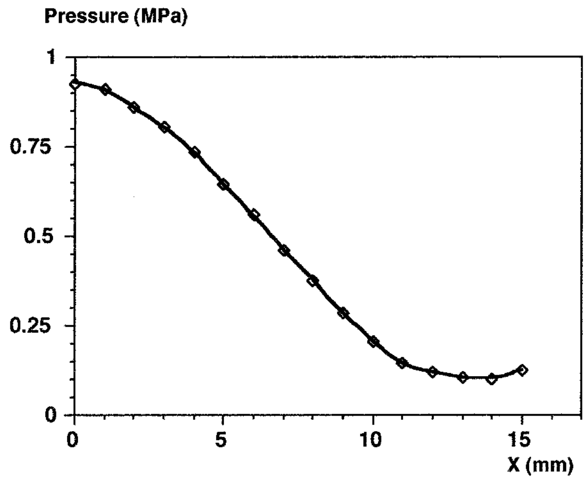

Fig. 3. Off-axis pressure field distribution for 0.92 MPa focal pressure.

up gave pressures of the order of 1 MPa at the focal point of the transducer, as shown in the pressure diagram (Fig. 3) which was obtained using a PVDF membrane hydrophone with an active element of 0.5 mm (Marconi).

3.3. The measurement cell

The measurement cell (Fig. 4) was made up of a Perspex tube (internal diameter 90 mm, thickness 5 mm and length 20 mm) containing the electrodes. Its two sides were formed by stretching and gluing on latex membranes to act as an acoustic window. The sodium chloride solution (9 g/l) was introduced into the cell through two silicon tubes, and once it had been filled, it was suspended in the tank full of degassed water. Micromanipulators with a track of 18 mm allowed displacement of the cell through the ultrasound field along X, Y and Z axes, and the tank had a positioning system to allow adjustment of its orientation in the ultrasound field. Two different pairs of electrodes were used; one pair for supplying the current and the other pair for measuring the voltage. This is a usual practice in the domain of making measurements of biological impedance, mainly because it avoids all the phenomena associated with polarization of the electrodes. In fact, for this work in particular, any effect that the ultrasound might have on electrode polarization impedance would not have had any great impact on the measurements. The electrodes consisted of four parallel and aligned stainless steel rods, 1 mm in diameter and 78 mm in total length. They were located in the middle of the measurement chamber, perpendicular to the beam axis and in symmetrical positions with respect to the latter. The outermost electrodes were used for current injection and the other two for voltage sensing. Only their central part was active and they were covered with an insulating polyethylene sheath with an external diameter of 1.6 mm. The current supply electrodes had an active length of 10 mm and were separated by a distance of 7 mm. The voltage measurement electrodes had an active length of 3 mm and were separated by a distance of 3 mm. To keep the measuring wires out of the ultrasound field, they were soldered onto the ends of the electrodes which were stuck inside the Perspex cylinders. These cylinders were fixed into special holes bored into the tube which made up the framework of the tank.

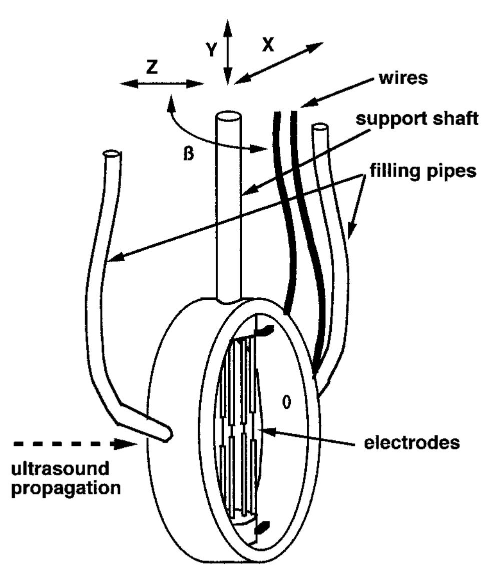

Fig. 4. The measurement cell.

3.4. Current generator

In purely theoretical terms, to detect the AEI signal, it would be ideal to be able to use direct current to obtain a high-frequency signal. However, direct current has certain major disadvantages in that it induces electrode polarization which is exacerbated by the effects of electrolysis. In order to avoid these problems, it was decided to work with low-frequency alternating current with a symmetrical, rectangular wave form with a frequency of 100 Hz.

The signal generator (Hewlett Packard type 8112) used for this current was synchronized with the ultrasound generator in such a way to ensure that the ultrasound pulse was emitted 2.5 ms after the ascending front of the low-frequency signal so that any transient electrical phenomena would have disappeared by the time the pressure wave arrived at the measurement area. A voltage–current converter driven by the rectangular signal was used to maintain a constant current (12 mA maximum value) through the solution. The direction of the current could be reversed by reversing the polarity of the signal generator.

3.5. Signal measurement

The voltage measurement electrodes were connected to the input of a specially fabricated differential amplifier designed for electrical impedance tomography [17,18]. This amplifier had a gain of 100, a −6db bandwidth of 2 MHz, a differential input impedance of 660 kΩ and a shared mode rejection rate of 60 dB. After the amplifier, there was a pass-band filter with a central frequency of 500 kHz and a −6db bandwidth of 100 kHz. The signals coming from the amplifier and the filter were passed into a digital oscillator (Tektronix 2430A) with a sampling frequency of 100 MHz. In order to reduce the background noise, the signals measured were averaged using the oscilloscope's internal averaging system. All signals measured on the oscilloscope could be printed out from the plotter or recorded on diskette via the IEEE interface.

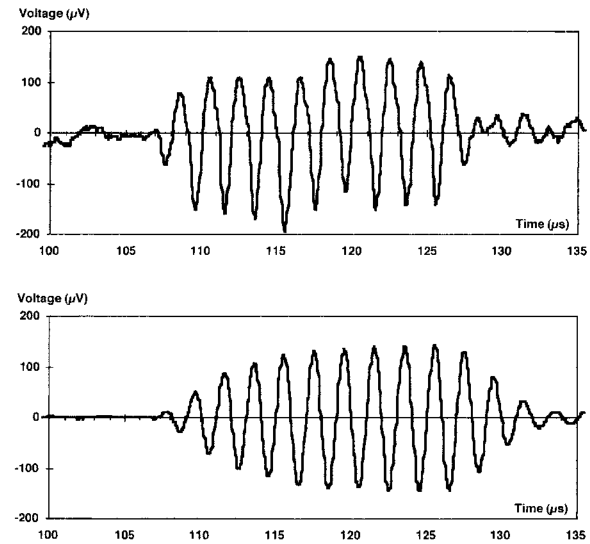

Fig. 5. Example of measured and averaged signal: the upper signal corresponded to the amplifier output, the lower signal corresponded to the filter output. The amplitude scale corresponded to the magnitude of the signal between electrodes.

4. Methods

The goal was to investigate the feasibility of measuring the AEI signal and then follow its variation with pressure and current.

The measurement cell was filled with a 0.9% sodium chloride solution and submerged in the tank. It was oriented so that the plane of the electrodes was perpendicular to the ultrasound propagation axis, and the micromanipulators were used to position it with its center (i.e. the active part of the measurement electrodes) within the transducer's focal area. A symmetrical, rectangular 12 mA current was passed between the electrodes, and the measurement cell experienced a sinusoidal acoustic pressure of an amplitude of 0.92 MPa as measured at the focal point. A signal was observed on the oscilloscope screen but the background noise was too high. When the oscilloscope's internal averaging system was activated, the signal became much clearer and it was observed at the moment at which the ultrasound pressure wave reached the measurement zone defined by the electrodes. As can be seen in Fig. 5, the form and duration of the signal closely correspond to the acoustic pressure pattern.

The point at which the signal was largest was determined by adjusting the orientation and varying the measurement cell's position (using the X and Y micromanipulators). This point was taken as the reference position for all the measurements discussed in this work. It was observed that the maximum was not obtained when the direction of the current was perpendicular to the ultrasound propagation axis, but rather at an angle of about 80° to it.

In order to check that the observed signal was indeed due to the ultrasound, several basic tests were conducted:

- Ultrasound emission was interrupted; this caused the signal to disappear.
- Using the micromanipulators, the measurement cell was displaced a known distance along the ultrasound propagation axis; the signal was observed to be delayed by the appropriate time factor.
- Using the micromanipulators, the measurement cell was displaced a known distance along the *X*-axis in order to move it out of the focal plane; the amplitude of the signal was observed to diminish.
- The phase of the ultrasound drive signal was reversed (a 180° phase change); the phase of the signal was observed to be reversed.

In order to check that the observed signal was indeed dependent on the current, the direction of the current was reversed. Instead of the signal getting reversed, as expected, a major decrease in its amplitude was observed. The most likely explanation for this apparent asymmetry was that there was some other signal which was positively interfering with the signal due to acoustic pressure-dependent changes in conductivity. This hypothesis was confirmed when the current between the electrodes was switched off and a signal corresponding to the acoustic pressure pattern was still detected. This signal is due to a Debye effect vibration potential at the electrodes in the ultrasound field.

Therefore, these two different signals, both of which were contributing to the readings, had to be resolved. Assuming that the Debye effect was not affected by the current passing between the electrodes, it was decided to make two separate, successive measurements of the signals at the electrode terminals for every data point: first, to quantitate the Debye effect signal, in the presence of an ultrasound field but without any current passing through the solution, and second, with both the ultrasound field and the current. The signal resulting from acousto-electric interactions (i.e. between the ultrasound waves and the current) corresponds to the difference between these two measurements.

Results are presented after amplification and filtering, and all results pertaining to the voltage at the electrode terminals have been normalized by dividing the measured signal by the gain of the instrument used.

5. Results

5.1. Measurements (taking the Debye effect voltage into account)

The signal at the electrode terminals was measured, without any current and with the measurement cell at different positions along the X-axis, for a series of different acoustic pressure levels. Fig. 6 shows the variation of the signal as a function of the position on the X-axis at a series of different focal point acoustic pressure levels. These readings gave curves which corresponded to the off-axis pressure field distribution.

For a focal pressure of 0.92 MPa, electrode terminal voltages were measured with a current of 12 mA passing in both the directions with the measurement cell at different positions along the X-axis. Fig. 7(a) shows the amplitude of the signal as a function of the cell position with and without applied current. In order to determine the signal resulting from acousto-electrical interactions, the signal measured in the absence of any current (i.e. the signal due to the Debye effect) was subtracted from that measured with the current flowing. Fig. 7(b) shows the resultant curve as a function of the measurement cell's position along the X-axis: data points generated with the current moving in each direction form quasi-symmetrical curves both of which resemble off-axis pressure field distribution of the transducer.

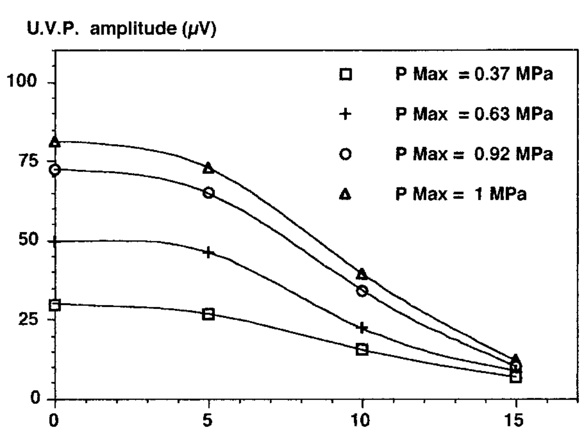

Fig. 6. UVP diagrams for different focal pressures.

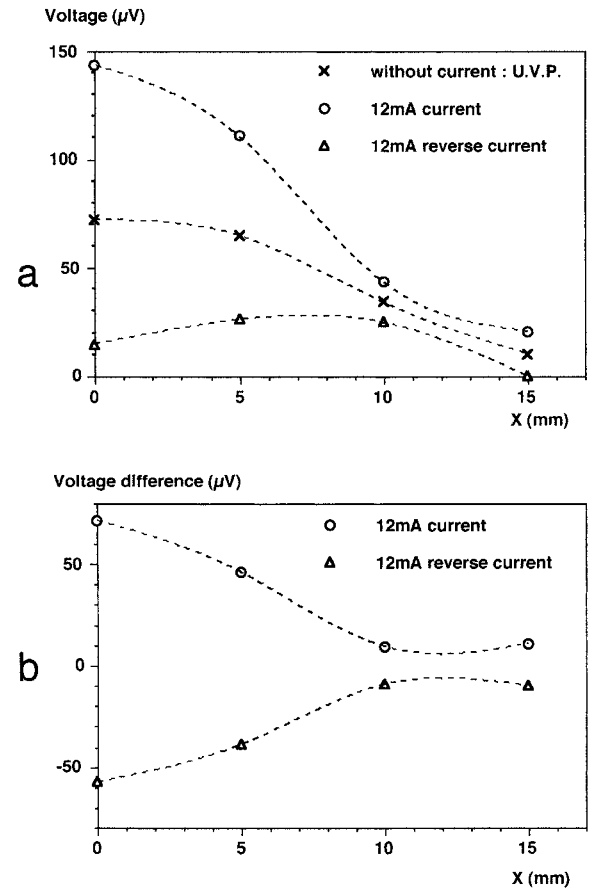

Fig. 7. (a) Amplitude of the measured signal with current applied and without current (UVP) as a function of the measurement cell position along X-axis for a 0.92 MPa focal pressure. (b) Amplitude of the AEI signal after having subtracted the UVP signal from the measured signal as a function of the measurement cell position along the X-axis.

Henceforth, only resultant signals (i.e. "the signal measured in the presence of current" minus "the signal measured without any current") will be presented.

5.2. Relationship between AEI signal and pressure

In order to follow the variation of interaction signal with acoustic pressure, the signal at the voltage electrode terminals was measured – with the measurement cell at different positions along the X-axis – at a series of different energy levels corresponding to focal point pressure readings of 0.37, 0.63, 0.92 and 1 MPa. Measurements were made for currents of 1.5, 3, 6 and 12 mA traveling in each direction. In Fig. 8, the

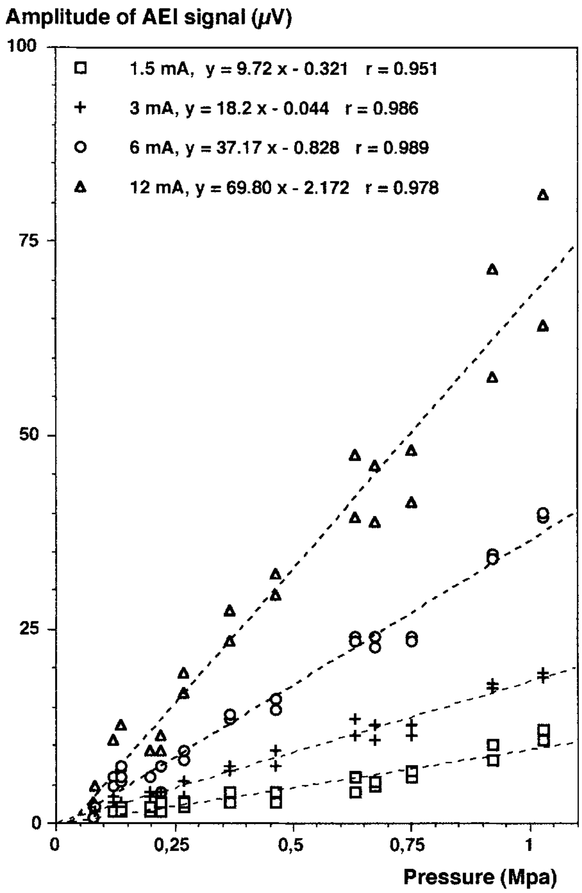

Fig. 8. Amplitude of the AEI signal as a function of acoustic pressure for different current values.

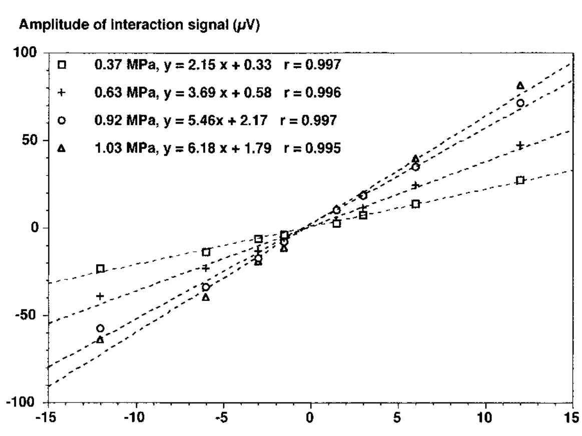

Fig. 9. Amplitude of the AEI signal as a function of current for different focal pressure values. The current is arbitrarily defined as positive when the measured signal voltage is greater than the UVP signal value.

amplitude of the interaction signal is shown, for each different amount of current, as a function of the acoustic pressure at the center of the measurement zone. At each different current value, the readings fall on a line, and linear regression analysis, in every case, yielded a straight line, which passed close to the origin and gave a correlation coefficient of over 0.95. As far as the slope of these linear regression analyses is concerned, for every doubling of the current, the linear regression changed by more or less the same factor.

5.3. Relationship between AEI signal and current

Taking only those results pertaining to measurements made at the focal point, the variation of AEI signal with current is shown in Fig. 9. The direction of the current for which the measured electrode terminal voltage was greater than the Debye effect voltage was considered as positive. At each of the four different pressure levels, all of the experimentally measured points fall on a line and linear regression analysis, in every case, yielded a straight line which passed close to the origin and gave a correlation coefficient of over 0.99. The slopes of the various linear regression analyses were all more or less proportional to pressure.

5.4. Determination of an apparent interaction factor

The fact that the interaction voltage is proportional to both pressure and current makes it possible to derive an apparent interaction factor. For every single data point, the ratio of the interaction voltage to the acoustic pressure was calculated and plotted against current (Fig. 10). Linear regression analysis of these data gives a straight line which passes close to the origin and gives a correlation coefficient of over 0.97. The slope of this line is the apparent interaction factor (5.3 $\mu V\,mA^{-1}\,MPa^{-1}$).

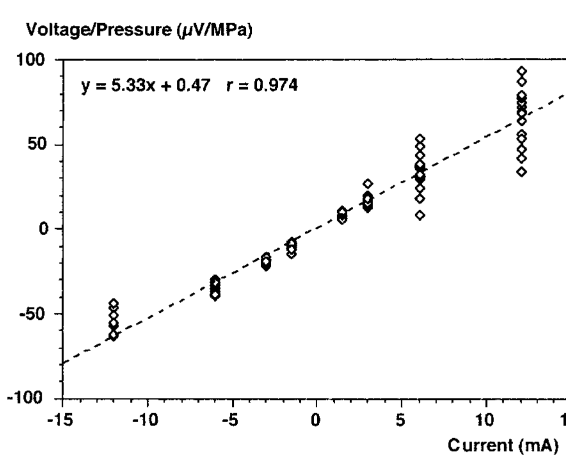

Fig. 10. Ratio of the interaction voltage to the acoustic pressure as a function of current.

6. Discussion and conclusions

In the present experimental conditions, the voltage between the electrodes was the addition of two effects: the changes in the conductivity of the medium due to the presence of a pressure wave and the vibration potential due to the Debye effect. Both these voltages depend on acoustic pressure, and in order to derive only the AEI signal, it is necessary to measure and subtract the Debye component (which is present whether or not there is any current) from the overall voltage measured experimentally when a current is flowing. We are not aware that attention has been drawn to this point previously.

Insofar as the direction of the current path with respect to the ultrasound propagation axis is concerned, it is certain that finding the best orientation for the measurement cell by identifying the point at which the voltage is highest is far from ideal, because the point thus identified is only that where the sum of the Debye and acousto-electric interaction components is at its greatest. Given the configuration of the electrodes used, the ultrasonic vibration potential would be at a maximum when the distance between the measurement electrodes projected onto the ultrasound propagation axis was equivalent to one half wavelength. In this series of experiments, the plane of the electrodes was at a 60° angle to the ultrasound propagation axis, whereas the Debye effect is at a minimum if this angle is 90° (confirmed experimentally). For the measurements made, the path of the current was not perpendicular to the ultrasound propagation axis but rather at an angle of about 80°. Of course, if measurements had been made at 90°, the voltage due to changes in the conductivity of the solution would have been at a maximum [11], but still there would have been a Debye effect component, which would have been very small and therefore difficult to measure. In this case, the fact that such measurements can actually contain two different components would never have been detected.

With respect to the measurement volume defined by the two electrodes, the fact that it is not exactly defined in space, especially in the direction of ultrasound propagation, shows that the electrode configuration chosen did not maximize the AEI signal due to pressure-induced changes in conductivity. Since successive positive and negative pressure waves induce both an increase and decrease in conductivity, it is possible that these might be sensed by the electrodes at the same time which would attenuate the AEI signal, possibly to a significant extent. For this reason, it is only possible to define an apparent interaction factor which is specific to the configuration of the electrodes used for these measurements.

It might be asked whether the presence of electrodes in the pressure field might not give rise to electrode effects at the interfaces with the conducting solution. Given that a constant current is supplied to the external electrodes, any change in their polarization impedance would only induce minor voltage changes at the electrodes. Any such minor changes would have little impact on the measurement electrodes due to the use of the four-electrodes technique. Moreover, using a differential measurement system tends to cancel out such electrode effects.

With respect to "false" and "junction effects" like those involved in the measurement of the Debye effect and discussed by Rosenfeld et al. [19], Millner [14] and Zana [15], the fact that the electrodes used were relatively long means that the acoustic pressure at the points where they are fixed into the framework is low (actually close to zero) which helps cut down "false effects". Moreover, the fact that the signal measured in the absence of current is subtracted from the signal measured in the presence of current tends to reduce the impact of such "false" and "junction effects" on the final result.

Heating of the medium would lead to variations in conductivity but these measurements were performed in a medium which absorbs ultrasound inefficiently and with a wave pulse of short duration (20 μs) in comparison to its recurrence frequency (100 Hz) such that the solution temperature did not change significantly.

In conclusion, these experiments have shown that it is possible to measure the AEI signal which results from ultrasound-induced changes in the conductivity of a conducting solution. It has been shown that it is necessary to determine and subtract ultrasound vibration potential effects if the AEI signal due to conductivity changes is to be measured accurately. These results show that the AEI signal is directly proportional to both current and acoustic pressure in the conditions adopted for this series of experiments.

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