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Enhancement of Acoustic Properties of Ultrasound Matching Material between Probe and Soft Tissue

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ABSTRACT

Materials with acoustic parameters like soft tissue are essential, such as Tissue-Mimicking Materials for diagnostic ultrasound. Acoustic parameters consist of the sound velocity, acoustic impedance, and attenuation coefficient. In this study, the acoustic impedance of linseed gel is improved to be more suitable than traditional gel. The acoustic impedance of traditional gel is about 1.48 MRayl, although the average acoustic impedance of soft tissue is 1.633 MRayl. This difference in impedance between gel and soft tissue increases the amount of reflection at the interference between the probe and the skin of patient. Thus, the transmission of ultrasound into the patient decreased, which negatively affected the quality of the resultant image. This paper presents a new material whose acoustic impedance is close to 1.633 MRayl based on a Non-Destructive Testing system. The sound velocity and density of linseed gel were estimated using the pulse-echo technique at 20˚C in National Institutes of Standards, Cairo, Egypt. The acoustic quantities of linseed gel were calculated in laboratory at frequencies 4 MHz. The acoustic impedance is improved from 1.39 MRayl to 1.598 MRayl, which is more suitable than traditional gel and it could resemble soft tissue for ultrasound. Improving Ultrasound image can be achieved by using the proposed enhancement material.

1. INTRODUCTION

The acoustic impedance of a material is one of the most common parameters. Acoustic impedance is the product of the density and speed of a tested material as a matching medical phantom. Acoustic quantities of Tissue Mimicking Material (TMM) are very important parameters to confirm its compatibility with medical matching material [1, 2]. It differed between soft tissues and hard tissues. Thus, the measured value of density and ultrasound velocity described how much resistance an ultrasound beam encountered as it passed through a tissue [1, 3].

Any improvement in ultrasound image is an important step in diagnosis and treatment. Ultrasound scanning uses sound waves to build images of the organs inside the body. It used a small probe called a transducer and a matching material, which was placed directly above the skin. Sound waves traveled from probe to human tissue through the matching material, which helped to reduce the reflection of ultrasound waves. The intensity reflection coefficient between two media could be obtained by Equation (1) [4, 5].

$$R = \left[\frac{z2 - z1}{z2 + z1}\right]^2 \times 100\% \tag{1}$$

where R is the intensity reflection coefficient, $z1$ is the acoustic impedance of the first medium and $z2$ is the acoustic impedance of second medium. The higher enhancement of the resultant images is increased with decreasing the value of R, which is used to help with medical diagnoses and detecting the change in appearance of organs and tissue. The value of R for the traditional gel–soft tissue is 0.02326 [6]. We can reduce this value by letting the values of $z1$ and $z2$ as close as possible and consequently a better image quality. Therefore, a coupling medium between ultrasound transducers and soft tissue such as gel or oil is needed. The common materials that were used as matching material are Aloe Vera (AV) juice proposed by Ghouhan R. S. *et al.* (2016) which reached 1.566 MRayl [7], Agar gel sample with Super-Paramagnetic Iron Oxide Nanoparticles proposed by A. Jozefczak which achieved 1.52 MRayl [8]. It is better than pure gar gel which gives 1.48 MRayl [4]. Silicon rubber proposed by Ashraf A. W. *et al.* 2013 [4] whose acoustic impedance is 1.54 MRayl [6]. Finally, Konjac Glucomannan gel proposed by Anis Naziah which reached 1.559 M Rayl [3, 9-11].

In this proposed work, the improvement is based on using a matching material to mix linseed oil and linseed gel. This material had been put between the ultrasound transducer and the soft tissue. The intensity of reflection coefficient for the incident ultrasound beam decreased, and then the transmitted ultrasound signal that passed through the tissue will be increased. This improvement of ultrasound image can be shown by measuring some acoustic parameters. These parameters are ultrasound velocity (U), density (ρ), and attenuation. These acoustic parameters show the good performance of linseed gel material which is used in ultrasound imaging measurements [12]. In this work, acoustical quantities of linseed gel are U, z and ρ which were measured inside National Institutes of Standards, Cairo, Egypt using pulse echo technique.

2. METHODOLOGY

In this section, we describe how to extract the proposed matching material (linseed gel) from the seeds. Linseed, also called flaxseed, is an important oilseed in the world. It is grown, for example, in Canada, America, China, and India [13, 14].

The dermatological safety of linseed (flaxseed) extracts and oils, which are widely used in cosmetic and pharmaceutical formulations. Additionally, we clarified that our assertion is based on the well-documented biocompatibility and hypoallergenic properties of linseed components [15].

Linseed gel material is used as a matching layer material between probe and soft tissue which improves ultrasound imaging [13]. A linseed gel consists of omega-3 fatty acids, and it has no side effects on human skin. As shown in **Figure 1**, the first step is placing, for example, 500 milligrams of linseed seeds in a bowl with 500 milliliters of distilled water. The second step is bringing the linseed seeds and the distilled water into a pan and letting them boil to 100˚ Celsius. After around 7 - 10 minutes, the mixture becomes tan colored. Finally, pour the mixture through a strainer lined with a suitable mesh to get more gel and get rid of the seeds. The experiment was performed as shown in **Figure 2**.

The calculations begin with a fixed frequency 4 MHz and temperature at 20˚C.

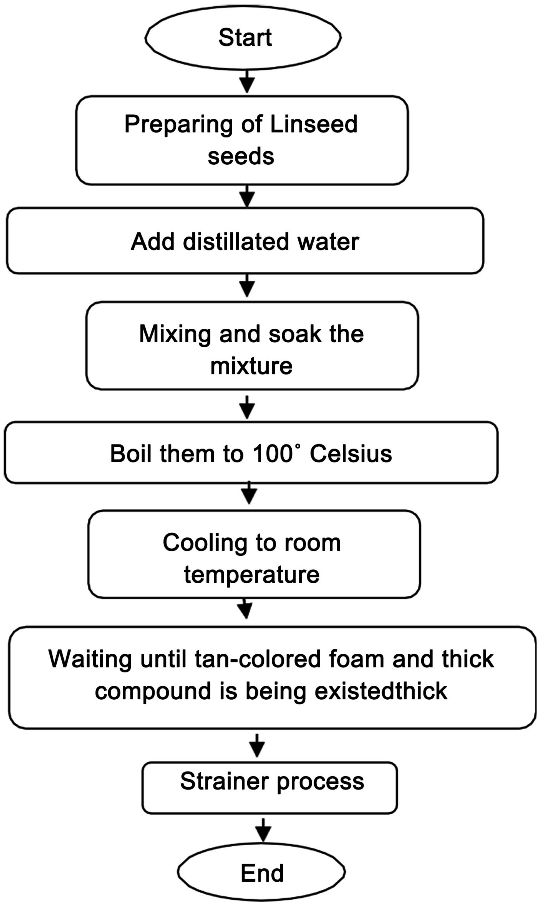

Figure 1. The flow chart of material preparation.

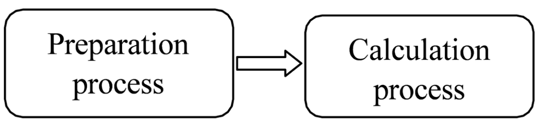

Figure 2. The block diagram for experimental techniques.

3. EXPERIMENTAL TECHNIQUES

The second process is calculation process, in which Density (ρ), ultrasound velocity (U) and acoustic impedance (z) of the samples were measured inside NIS, Cairo, Egypt by using the following standard from relation (z) to relation (4) [7, 16].

$$\rho = \frac{m}{v}.\quad \text{kg}\cdot\text{m}^{-3} \tag{2}$$

The ultrasound velocity was measured for the sample inside the Ultrasound department of NIS, Cairo, Egypt. Micrometer is used for measuring the velocity according to pulse echo technique by the following relation (3) [16].

$$U = \lambda \times f = X/T.\quad \text{m/sec} \tag{3}$$

where λ is the wavelength, f is the frequency, T is the time taken between two echoes from transmitter and receiver and X is the distance of the sample of linseed gel.

In the year 1952, Jacobson suggested a relation for knowing the value of intermolecular free length (L_F)

of liquids by using the following standard from relation (5) [7, 16-18] to relation (4) [7, 16-18]. Adiabatic compressibility (β_a), L_F and bulk modulus (k) were calculated and measured using the following standard relations (5) [7, 16-18] and (7) [16-18].

$$z = \rho \cdot U \quad \text{Kg/(m}^2\text{·s)} \tag{4}$$

$$\beta_a = 1 \big/ \left[U^2 \cdot \rho \right] \quad \text{(s}^2\text{·m)/Kg} \tag{5}$$

$$L_F = k \big/ \left[U \cdot \rho^{0.5} \right] = k \cdot \beta_a^{0.5} \tag{6}$$

Adiabatic compressibility is the property of being reduced to a small area by pressure. The compressibility of fluid can be defined as the measure of the change in density that will be produced in the fluid by a specified change in pressure. Bulk modulus determines how compressible a system is. It is the inverse of compressibility as shown in the following relation.

$$k = U^2 \cdot \rho \tag{7}$$

where the constant k is called Jacobson's constant which depends on temperature (k value for different temperature were taken from the work of Jacobson) [16-18]. It is given by relation $K = (93.875 + 0.375t) \times 10^{-8}$. And ($t$) is the absolute temperature. The experiment was performed at fixed frequency 4 MHz and at temperature at 20˚C. The selection of 4 MHz was intentional because this frequency is widely applied in diagnostic ultrasound imaging of soft tissues.

4. RESULTS AND DISCUSSION

The enhancement of acoustic properties using a linseed gel as a matching material resulted in decreasing the reflection intensity coefficient R of Equation (1), as shown in **Table 1**, as follows.

The intensity reflection coefficient $R = 0.009827$ for linseed gel, $R = 0.2326$ for water-gel and $R = 0.048152$ for silicon oil [4, 5]. Therefore, the intensity reflection coefficient of the enhanced material (linseed gel) is smaller than the intensity reflection coefficient of the traditional gel and silicon oil. Consequently, ultrasound image enhancement should be achieved by using linseed gel as a matching material between probe and soft tissue. Where the acoustic impedances of the materials used in measurements are as shown in **Table 2**, as follows.

Table 1. The reflection intensity coefficient using linseed gel compared to other materials.

Material	Air-Tissue	Water (Gel)-Tissue	Silicon rubber-Tissue	Linseed Gel-Tissue
R (%)	99.902	0.2326	0.048152	0.009827

Table 2. The acoustic impedance of some materials.

	Air	Water (Gel)	Soft Tissue	Silicon rubber	Linseed Gel
z (MRayl)	0.0004	1.48	1.633	1.561	1.598

It is seen from **Table 1** that the percentage energy reflected is almost 23.59 times smaller for linseed gel /tissue acoustic barrier than it is for water (gel)/tissue barrier. And the percentage energy reflected is almost 4.26 times smaller for linseed gel/tissue acoustic barrier than it is for silicon rubber barrier. It explains that the efficiency of the diagnostic imaging is increased by about twenty times when using a mixture of linseed oil and linseed gel instead of gel material. Also, it is more suitable than silicon oil, whose acoustic impedance is 1.561 MRayl. Silicon oil is difficult to remove from the skin [4, 5] but Linseed gel is safer on skin and easily removed from the skin of patients.

Figure 3 shows that the acoustic impedance of linseed gel reaches 1.598 MRayl, which is higher than that of conventional ultrasound gel (water gel) which is equal to 1.48 MRayl. It is close to the acoustic impedance of the average soft tissue which is 1.633 MRayl. The proposed work evaluated this result through the five features discussed in previous sections as follows: The values of ρ and U are used to calculate values z, β_a, L_F, K and k as a function of concentration for the different samples in **Table 3**.

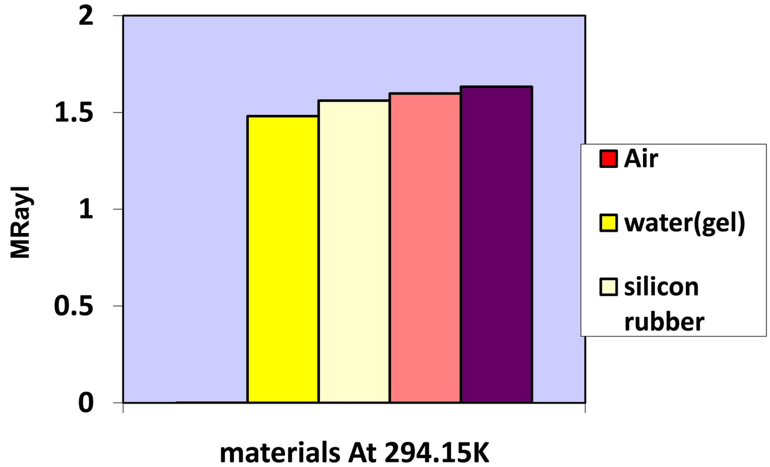

Figure 3. Acoustic impedance of materials at 4 MHz.

Table 3. The acoustic impedance of samples (1-5).

samples	Linseed gel	Linseed oil (1)	Linseed oil (2)	Ultrasound velocity (m/s)	Density (g/cm^3)	Acoustic impedance (M. Rayls)	Adiabatic compressibility $\beta a \times 10^{-10}$	Inter-molecular free length Lf (A^0)	Bulk modulus $K \times 10^9$ (N·m^{-2})
1	-	100%	-	1503	0.92828	1.39	4.768	0.449	2.098
2	-	-	100%	1480	0.94624	1.40	4.824	0.452	2.073
3	100%	-	-	1506	0.97562	1.469	4.519	0.437	2.212
4	90%	10%	-	1495	1.02113	1.526	4.3816	0.430	2.821
5	75%	25%	-	1601	0.99846	1.598	3.9073	0.406	2.534

Start searching for material that has a closer value to the acoustic impedance of soft tissue by using Non-Destructive Testing system (NDT). It is measured by two samples of linseed oil (sample 1 and sample 2). The value of acoustic impedance of linseed oil (sample 1) was enhanced to be a more suitable material as a sonar gel. Also, acoustic quantities of linseed oil were calculated with a density 0.92828 g/cm^3, sound speed 1503 m/s.

In the beginning, two different linseed oils which give different values of velocity, density, and acoustic impedance according to their purity, as shown in **Table 3**, with a high acoustic impedance equal to 1.40 MRayls. Linseed oil is difficult to use alone on the skin of patients as a sonar gel because it is hard to remove from the skin so, Linseed gel is extracted to be more suitable for use.

The aim of this paper is to enhance the acoustic impedance value with respect to the material texture. After preparation of the linseed gel (based on water), which was presented in material preparation section, the velocity, density, and acoustic impedance are shown in **Table 3**, giving higher performance than the two previous linseed oils (samples 1 and 2). Density, velocity, and acoustic impedance of linseed gel were measured inside INS, Cairo, Egypt.

The ultrasound velocity of the linseed gel (sample 3) is 1506 m/s. The density of linseed gel is 0.975627 g/cm^3. The acoustic impedance of the linseed gel (sample 3) is 1.469 MRayls. It is higher than the previous two linseed oils but still lower than 1.48 MRayls [4] which is the current traditional gel. Repeat the steps of extraction of linseed gel (which is based on water) with an additional 60 milligrams of linseed oil (sample 1) to be (sample 4). The acoustic properties were measured inside INS, Cairo, Egypt. The ultrasound velocity of the linseed gel (sample 4) is 1495 m/s. The density of linseed gel is 1.02113 g/cm^3. The acoustic impedance of the linseed gel (sample 4) is 1.526 MRayls.

The acoustic impedance of Linseed gel based on oil is higher than the acoustic impedance of Linseed gel based on water. It is noticed that the higher concentration of linseed oil in the mixture gives a higher acoustic impedance value. Finally, repeat the last step with an additional 125 milligrams of linseed oil to be sample [5] with respect to the material texture. The ultrasound velocity of the linseed gel (sample 5) is 1601 m/s. The density of linseed gel is 0.998463 g/cm^3. The acoustic impedance of the linseed gel (sample 5) is 1.5975408 MRayls. It gives better performance than all previous samples and is closer to the acoustic impedance of soft tissue under frequency 4 MHZ. The intermolecular free length increases with a decrease in ultrasonic velocity. Table [3] explains the weak interaction between the ion and solvent molecules of linseed gel. This is suggested by the increase in acoustic impedance and increase in adiabatic compressibility. Linseed gel has a lower value than linseed oil in adiabatic compressibility and intermolecular free length 3.907 and 0.406. Hence, it has a higher acoustic impedance than the linseed oils. The higher the value of bulk modulus, the more difficult it is to compress the fluid, as shown in table [3].

The main aim in this study is to enhance the acoustic impedance of linseed gel to close the ideal value of average acoustic impedance of soft tissue which equals 1.633 MRayl as shown in table [2]. The hybrid mixed between linseed gel and impure linseed oil is done. The different ratio of the linseed gel and linseed oil is used to enhance the acoustic impedance, as shown in table [3]. The best result of acoustic impedance when mixing linseed gel and linseed oil is 1.598 MRayl, which is presented in sample 5. It has a value close to the target value 1.633 MRayl when we use 75% from linseed gel and 25% from linseed oil [1]. We note that increasing ultrasonic velocity with increasing concentration of linseed gel in the mixtures at 4 MHz in 20˚C.

According to **Table 3**, the value of intermolecular free length decreases with an increase in ultrasonic velocity. Also, the value of adiabatic compressibility decreases with increasing ultrasound velocity and with increasing concentration of linseed gel. It explains the increase in acoustic impedance value of the fourth sample (75% linseed gel + 25% linseed oil) with 1.598 MRayl as shown in **Table 3** and **Figure 3**. It has closed the target value of 1.633 MRayl.

The need to investigate the long-term stability and shelf life of the linseed gel mixture, without preservatives (just seeds + water):

- At room temperature: Only a few hours before it starts fermenting or growing mold.
- In the refrigerator (4˚C): Typically, 3 - 7 days, depending on cleanliness during preparation. After that, it tends to be sour, separate, or moldy. So we suggest adding a preservative to the mixture in the future.

5. CONCLUSION

Improvement of the acoustic properties of matching material is one of the most important methods for ultrasound imaging enhancement. In this paper, a specific material (linseed gel) was proposed to be used as a matching layer between the ultrasound transducer and the soft tissue instead of the traditional gel. An extraction technique for gel from flaxseed was investigated, and it was added to linseed oil. The gel was mixed with the oil in a proportion of 75% and 25%, which gives a new material with an acoustic impedance close to soft tissue. Linseed gel played an important role in acoustic impedance matching between the ultrasound transducer and the diagnosed tissue. This method, using linseed gel can increase the efficiency of imaging processes by about fifty times compared to using water gel. This quality was evaluated using two calculated features: density and ultrasound velocity. These quantities had been improved by using linseed gel as an acoustic matching material. We have successfully determined ultrasound velocity, density, and acoustic impedance of linseed gel with three concentrations of linseed oil at 20˚C and 4 MHz. The acoustic impedance of linseed gel reaches 1.598 MRayl, which is higher than that of conventional ultrasound gel which is equal to 1.48 MRayl. It is close to the acoustic impedance of the average soft tissue which is 1.633 MRayl.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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