# Wideband frequency-dependent dielectric properties of rat tissues exposed to low-intensity focused ultrasound in the microwave frequency range

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Tissue dielectric properties can vary upon the incident of an acoustic wave. The goal of this study is to quantify this change due to the acoustoelectric effect (AE), and to obtain the frequency-dependent dielectric properties of tissues exposed to low-intensity focused ultrasound (LIFU). The dielectric properties of the blood, brain, chest muscle, heart, kidney, leg muscle, liver, lung, pancreas, and spleen of rats were measured by an open-ended coaxial probe method. The acoustic intensity of LIFU focus was 2.97 MPa (67.6 W/cm$^2$), 3.95 MPa (120 W/cm$^2$), and 5.17 MPa (204 W/cm$^2$), respectively, and the measurement frequency band was 0.1–7.08 GHz. The measurement results show that with the LIFU modulation, the conductivity and dielectric constant decreased in the high-frequency band, and on the contrary, they increased in the low-frequency band, and the larger the acoustic intensity was, the more obvious the phenomenon was. This work contributes to a better understanding of the mechanisms by which ultrasound acts on the dielectric properties of biological tissues. It is expected that the findings from this study will provide a basis that the response of tissue to LIFU modulation can be monitored by noninvasive techniques such as microwave-induced thermoacoustic imaging (MTI) and microwave imaging, present a new idea for improving the endogenous contrast between different biological tissues in MTI and acoustoelectric imaging, and possibly lead to the development of a new imaging method based on the relaxation time of tissue after LIFU modulation.

**Keywords:** dielectric property, rat tissues, low-intensity focused ultrasound

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## 1. Introduction

It is known that an ultrasound pressure ($P$) passing through the biological liquid or tissue causes a local change in electrical conductivity. This phenomenon is called the acoustoelectric effect (AE), which was firstly reported by Fox *et al.* in 1946.[1] A change in conductivity ($\sigma$) due to a pressure wave with amplitude $\Delta P$ can be written as

$$\frac{\Delta\sigma}{\sigma} = k_1 \Delta P, \tag{1}$$

where $k_1$ is an interaction constant whose value is roughly 0.01%–0.1% MPa$^{-1}$ in physiologic saline.[2,3] AE is a physical interaction between the acoustic and the electrical field, through which it changes the dielectric properties of tissue at the focal spot of the focused ultrasound.[2,4–6] AE has been recently used to realize the acoustoelectric imaging (AEI) of biological tissue which has been successfully applied for breast cancer detection,[7] cardiac imaging,[8–13] and mapping deep brain stimulation (DBS) currents during transcranial brain imaging.[14–19]

In parallel, in recent years low-density focused ultrasound (LIFU) has been studied as an alternative novel non-invasive brain stimulation technique.[20,21] It safely induces reversible AE in biological tissues and possesses dual advantages of exquisite spatial specificity and deep penetration.[22] Therefore, LIFU has great potential in improving clinical efficacy and replacing existing deep brain stimulation (DBS), transcranial magnetic stimulation, transcranial current stimulation, and other neuromodulation technologies.[23–25]

In both AEI and LIFU, there is a lack of quantitative understanding of how dielectric properties of tissue change over a wide range of frequencies. Such understanding can help us know the extent of the change of tissue dielectric properties so that appropriate ultrasound pressure can be determined for optimal AEI or LIFU neuromodulation. On the other hand, understanding how dielectric properties vary with frequency is also essential for a wide range of medical physics applications,[26–29] such as microwave-induced thermoacoustic imaging (MTI),[30–32] microwave imaging,[33,34] and microwave ablation.[35,36] Toward this end, in this study, we measured the frequency-dependent dielectric properties of *in vitro* rat blood, brain, chest muscle, heart, kidney, leg muscle, liver,

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lung, pancreas, and spleen tissues under three different LIFU field intensities and compared them to measurements under no ultrasound field.

## 2. Materials and methods

The measurement environment was kept at room temperature 25 °C and the microwave band was 0.1–7.08 GHz. The open-ended coaxial probe method[37–39] was used to measure the reflection coefficient and the conductivity and dielectric constant of tissues were calculated accordingly.

### 2.1. Preparation of biological tissues

In vitro blood, brain, chest muscle, heart, kidney, leg muscle, liver, lung, pancreas, and spleen tissues of rats were used as measurement samples, and each tissue was obtained from three different healthy adult male rats. All tissues were transported to our laboratory from the laboratory animal supply company within 2 hours after the extraction. During transportation, the samples were stored in a 5 °C refrigerator and wrapped with plastic film to minimize water loss as the dielectric constant significantly depends on the content and state of water in the tissues. The study protocol for animal experiments used in this research was approved by the Ethics Committee of the University of Electronic Science and Technology of China.

### 2.2. Dielectric properties measurement system

Compared to other methods for measuring dielectric properties, the open-ended coaxial probe method is more suitable for measuring semi-solid materials, such as biological tissues, because this method is non-invasive, requires simple sample preparation, and has a more convenient temperature control. In this study, a calibration involving open, short, and standard end liquid load terminations was used to eliminate the systematic errors of the open-ended coaxial probe method.[40] Open termination was established by placing the line in free space. Short termination was obtained by pressing the tip of the probe on an aluminum foil. To reach the standard liquid phase termination, the probe was immersed in deionized water, of which the dielectric properties are already known.[41]

As shown in Fig. 1, the electrical characteristic measurement system consists of a vector network analyzer (Agilent N9918A, Malaysia) and a semi-rigid probe with a size of 0.53 mm in/0.22 mm out connected to the network analyzer through a 1 m-length cable (415-0015-M1.0, Johnson-Cinch Co.) with a 50-Ω impedance. The measured data of the network analyzer is transmitted to the computer in real-time, where the dielectric constant and conductivity are calculated from the corrected complex reflection coefficient using the reasonable function model described in the literature.[37–39] The error calibration operation was performed before each tissue sample measurement. During the measurement, the other tip of the coaxial probe was completely in contact with the rat tissues (without insertion), and no air was allowed between the two tips as the presence of air may produce significant errors in measurement.[37–39] The sample was placed in a carrier sealed with thin plastic film at the bottom and then placed in a physiological saline bath, with the upper surface of the tissue exposed to air to prevent the physiological saline from interfering with the measurement results.

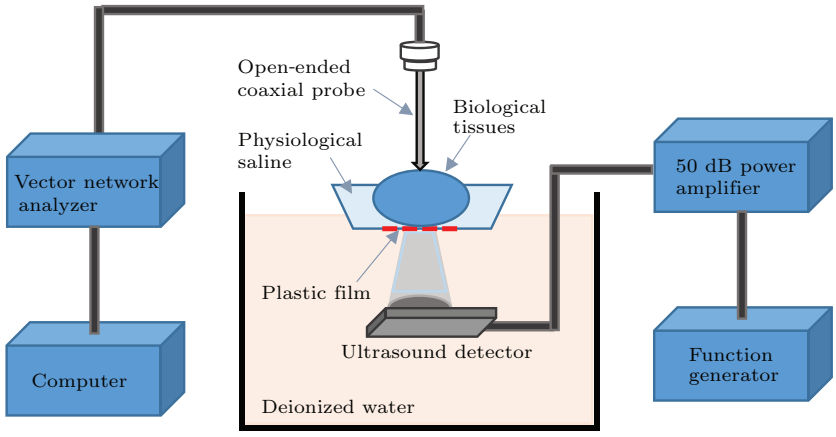



**Fig. 1.** Schematic diagram of the system for measuring the dielectric properties of rat tissues exposed to the LIFU field.

### 2.3. Low-intensity focused ultrasound generation system

As shown in Fig. 1, a 3.5-MHz single-element focused transducer ($d = 33$ mm, $f = 55$ mm, SU-102 S/N019, Sonic concepts) was immersed in a deionized water bath and focused on the sample from an inferior to superior view. A function generator (33220A, Agilent Technologies Inc., Santa Clara, CA) generated short negative square pulses (100 cycle burst, 250 μs duration) with 4-kHz repetition frequency, which was amplified by a 50 dB RF power amplifier (325LA, EN) and then used to excite the ultrasound transducer to produce an LIFU field. At the focal point, the peak pressures measured with a calibrated hydrophone (NH0500, Precision Acoustics Ltd, UK) were 2.97 MPa (67.6 W/cm$^2$), 3.95 MPa (120 W/cm$^2$), and 5.17 MPa (204 W/cm$^2$). The full-width

half-maximum (FWHM) of the pressure beam was 9.1 mm (axial) and 0.8 mm (lateral).

## 3. Results and discussion

### 3.1. Wideband analysis

Figures 2–11 show the mean electrical constants and conductivities and the corresponding standard deviations (SD) of ten in vitro rat tissues in the microwave range of 0.1–7.08 GHz for each of the nine measurements.

The dielectric constant and conductivity of nine types of tissues changed in varying degrees with modulation of the LIFU field, except for lung tissue (Fig. 9), which was minimally affected by modulation of the LIFU field. Specifically, under LIFU field modulation, the dielectric constant increased on the left side and decreased on the right side near 100 MHz (this frequency point varies with different tissues). The conductivity increased on the left and decreased on the right near 1.7 GHz (this frequency point varies with different tissues as well). Moreover, the greater the LIFU field energy, the greater the amplitude of increase or decrease at each frequency point. For each LIFU field, it was observed that in the frequency band higher than the cross points (100 MHz and 1.7 GHz), the variation amplitude of the dielectric constant affected by the LIFU field gradually decreased with the increase of the testing frequency, and it was speculated that a second cross point may appear at the position of a higher frequency.

In contrast, the amplitude of electrical conductivity under modulation of the LIFU field increased gradually with the increases in the testing frequency. The phenomenon of these cross changes may be caused by $\beta$ and $\gamma$ dispersion of

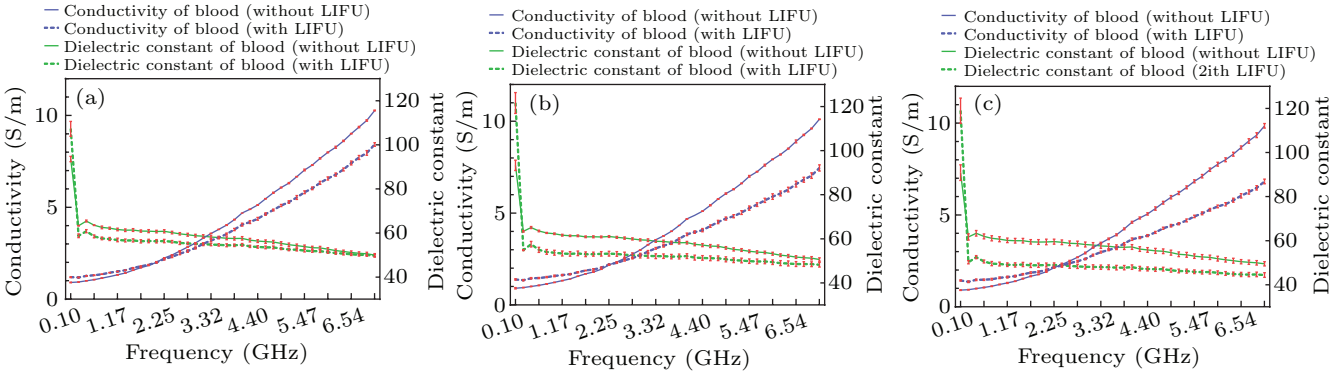



**Fig. 2.** Frequency-dependent dielectric properties of rat blood tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

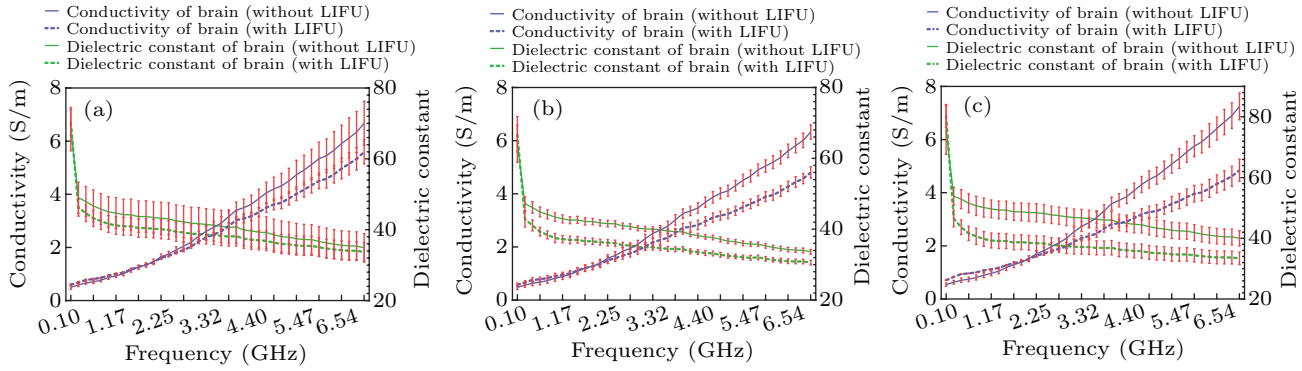



**Fig. 3.** Frequency-dependent dielectric properties of rat brain tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

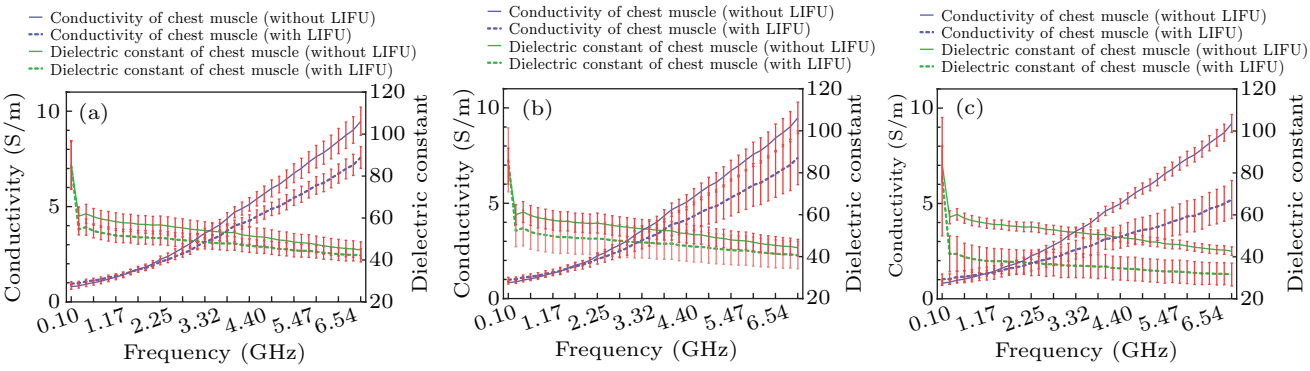



**Fig. 4.** Frequency-dependent dielectric properties of rat chest muscle tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

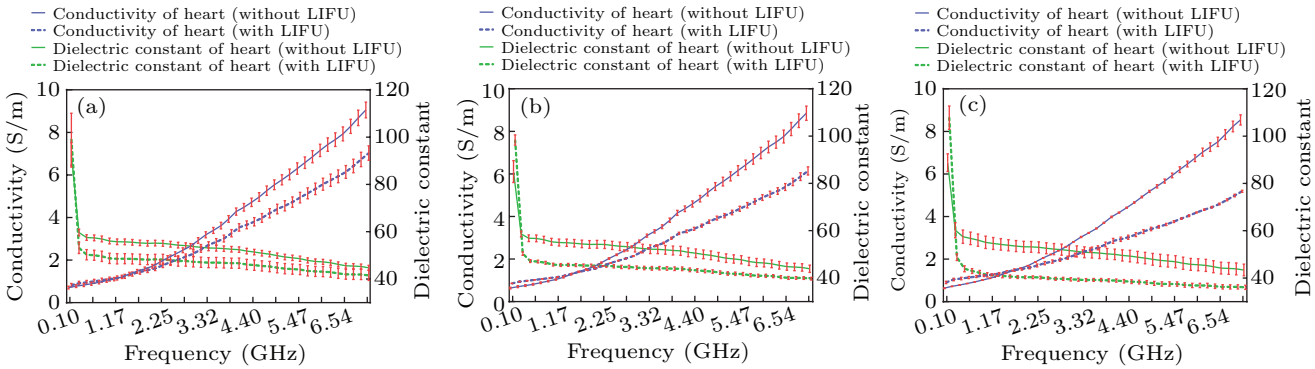



**Fig. 5.** Frequency-dependent dielectric properties of rat heart tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

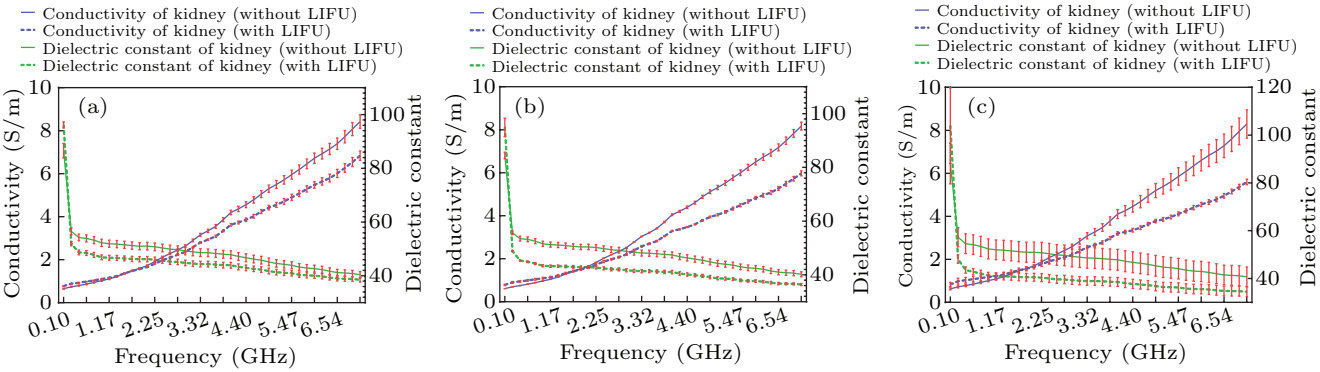



**Fig. 6.** Frequency-dependent dielectric properties of rat kidney tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

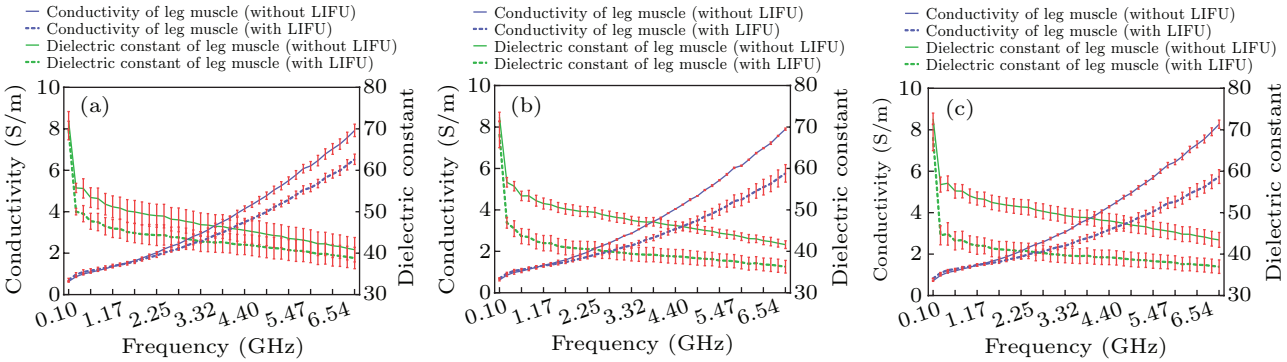



**Fig. 7.** Frequency-dependent dielectric properties of rat leg muscle tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

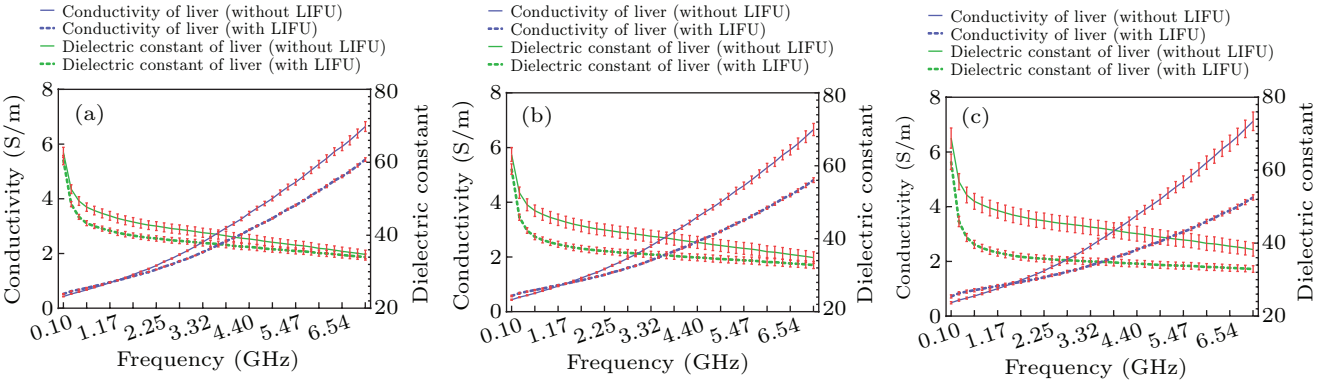



**Fig. 8.** Frequency-dependent dielectric properties of rat liver tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

biological tissue.[28,42] Except for the lung tissue, in vitro rat tissues measured in this study were composed of liquid (blood) or dense muscle, glandular tissue, and connective tissue (such as heart, chest muscle, leg muscle, pancreas, liver, kidney, etc.). Since these dense structures did not block the transmission of ultrasonic waves, LIFU had a significant modulation effect on them, showing obvious changes in dielectric properties. By contrast, the alveolar cavity structures in rat lung tissue were filled

with air, which might have impeded the transmission of ultrasound, and this may be the reason why the LIFU field had a minimal modulation effect on lung tissue.

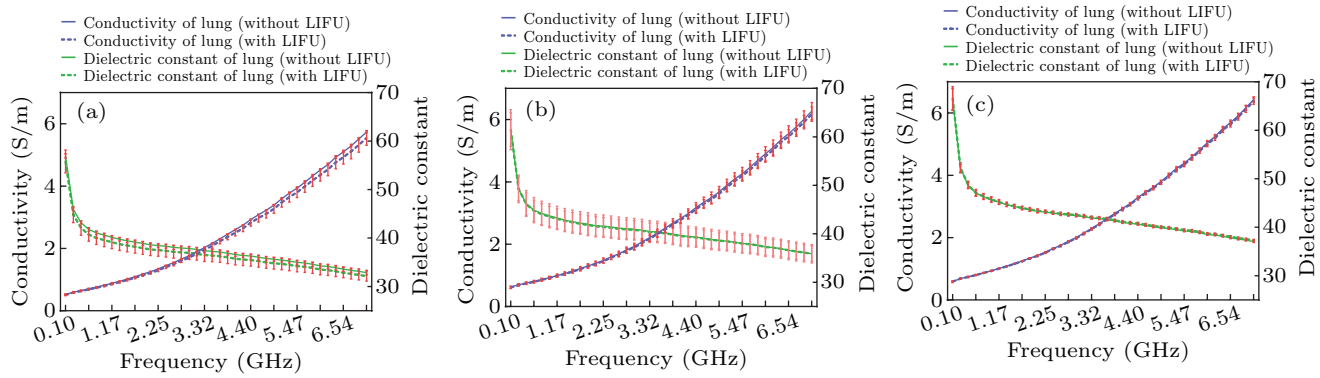



**Fig. 9.** Frequency-dependent dielectric properties of rat lung tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

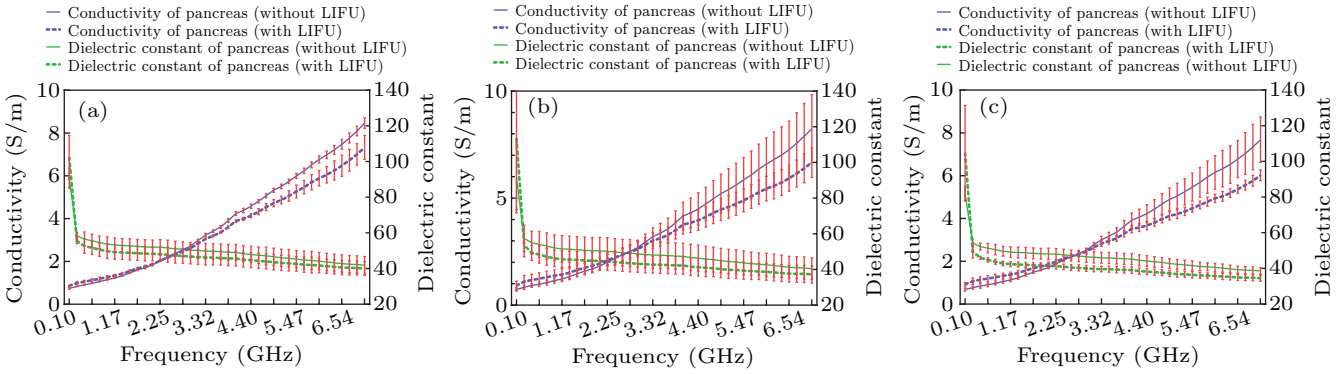



**Fig. 10.** Frequency-dependent dielectric properties of rat pancreas tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

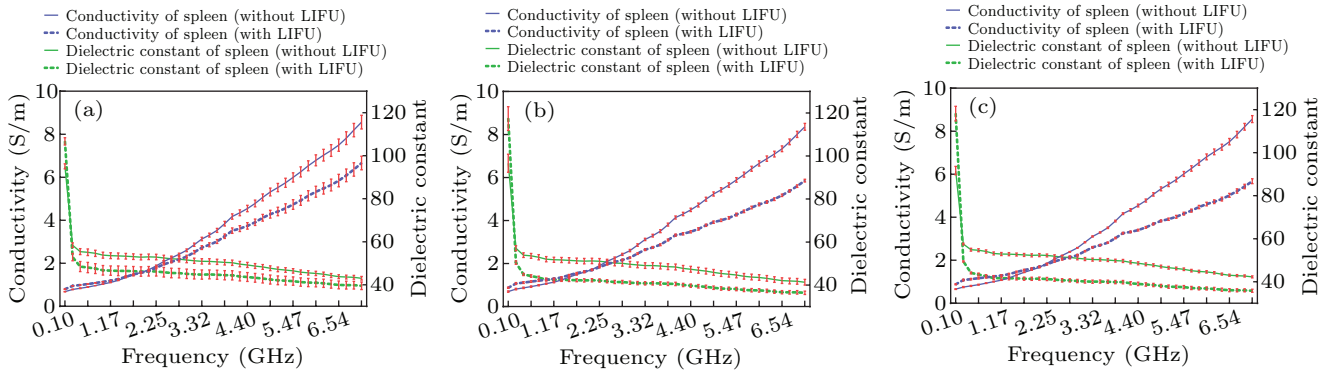



**Fig. 11.** Frequency-dependent dielectric properties of rat spleen tissue at (a) 67.6 W/cm$^2$, (b) 120 W/cm$^2$, and (c) 204 W/cm$^2$ peak pressure energies.

### 3.2. Single-frequency analysis

In order to quantitatively compare the changes of dielectric properties of *in vitro* rat tissues with and without modulation of the LIFU field, the average dielectric constant, conductivity, and corresponding standard deviation (SD) of each rat tissue at four microwave frequency points commonly used for MTI, namely, 458 MHz, 1.17 GHz, 2.96 GHz, and 6.01 GHz, are shown in Tables 1–4. SD of the measurements in the tables is in the range of 0.01 to 8.5.

**Table 1.** The dielectric property changes of rat tissues under ultrasound field measured at 458 MHz. DC: dielectric constant; CD: conductivity (S/m); SD: standard deviation.

| Tissues | | 67.6 W/cm$^2$ | | | | 120 W/cm$^2$ | | | | 204 W/cm$^2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD |
| Blood | DC | 65.43 | 0.43 | 60.85 | 0.72 | 65.12 | 0.44 | 57.59 | 1.26 | 63.36 | 1.24 | 52.54 | 0.68 |
| | CD | 1.00 | 0.01 | 1.27 | 0.02 | 1.01 | 0.02 | 1.45 | 0.04 | 1.00 | 0.02 | 1.47 | 0.04 |
| Brain | DC | 47.96 | 4.26 | 44.66 | 2.36 | 46.16 | 1.62 | 41.06 | 1.54 | 52.89 | 3.13 | 43.62 | 2.40 |
| | CD | 0.67 | 0.05 | 0.78 | 0.03 | 0.63 | 0.09 | 0.76 | 0.08 | 0.71 | 0.08 | 0.94 | 0.01 |
| Chest muscle | DC | 61.99 | 4.48 | 55.69 | 3.88 | 61.28 | 4.99 | 53.68 | 8.50 | 60.27 | 2.71 | 41.40 | 8.29 |
| | CD | 0.94 | 0.12 | 1.08 | 0.11 | 0.97 | 0.09 | 1.12 | 0.12 | 0.97 | 0.13 | 1.15 | 0.31 |

**Table 1.** (*Continued*).

| Tissues | | 67.6 W/cm$^2$ | | | | 120 W/cm$^2$ | | | | 204 W/cm$^2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD |
| Heart | DC | 57.53 | 1.19 | 50.28 | 2.16 | 56.80 | 1.41 | 47.16 | 0.58 | 57.47 | 2.81 | 43.92 | 1.26 |
| | CD | 0.83 | 0.72 | 0.96 | 0.09 | 0.75 | 0.04 | 0.98 | 0.01 | 0.78 | 0.01 | 1.09 | 0.06 |
| Kidney | DC | 54.25 | 1.25 | 48.72 | 0.89 | 53.48 | 0.92 | 45.32 | 0.23 | 54.53 | 4.12 | 43.53 | 1.33 |
| | CD | 0.80 | 0.03 | 0.93 | 0.01 | 0.76 | 0.01 | 0.95 | 0.04 | 0.78 | 0.05 | 1.03 | 0.13 |
| Leg muscle | DC | 55.63 | 2.33 | 49.53 | 1.95 | 55.72 | 1.13 | 45.49 | 1.90 | 57.10 | 1.76 | 44.88 | 2.71 |
| | CD | 1.00 | 0.05 | 1.09 | 0.11 | 0.98 | 0.08 | 1.07 | 0.06 | 1.12 | 0.04 | 1.23 | 0.03 |
| Liver | DC | 49.41 | 1.19 | 45.04 | 0.68 | 49.32 | 1.64 | 42.26 | 0.78 | 53.21 | 2.15 | 41.56 | 1.10 |
| | CD | 0.60 | 0.01 | 0.68 | 0.02 | 0.60 | 0.02 | 0.73 | 0.02 | 0.66 | 0.04 | 0.90 | 0.06 |
| Lung | DC | 43.19 | 0.24 | 42.08 | 1.49 | 46.25 | 2.65 | 46.14 | 2.29 | 48.68 | 0.62 | 48.73 | 0.77 |
| | CD | 0.65 | 0.02 | 0.63 | 0.02 | 0.75 | 0.04 | 0.74 | 0.03 | 0.74 | 0.02 | 0.74 | 0.01 |
| Pancreas | DC | 56.54 | 3.96 | 52.65 | 4.13 | 55.02 | 6.48 | 49.34 | 4.23 | 52.22 | 1.90 | 45.98 | 0.77 |
| | CD | 0.91 | 0.01 | 1.06 | 0.06 | 0.92 | 0.08 | 1.18 | 0.27 | 0.85 | 0.10 | 1.14 | 0.13 |
| Spleen | DC | 55.42 | 1.38 | 48.47 | 2.33 | 53.92 | 1.06 | 44.94 | 0.51 | 54.90 | 0.67 | 44.11 | 0.43 |
| | CD | 0.84 | 0.01 | 0.99 | 0.01 | 0.87 | 0.03 | 1.12 | 0.04 | 0.81 | 0.02 | 1.12 | 0.04 |

**Table 2.** The dielectric property changes of rat tissues under ultrasound field measured at 1.17 GHz. DC: dielectric constant; CD: conductivity (S/m); SD: standard deviation.

| Tissues | | 67.6 W/cm$^2$ | | | | 120 W/cm$^2$ | | | | 204 W/cm$^2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD |
| Blood | DC | 61.62 | 0.60 | 56.85 | 0.80 | 61.64 | 0.40 | 53.34 | 1.13 | 60.14 | 1.03 | 49.10 | 0.82 |
| | CD | 1.32 | 0.02 | 1.51 | 0.01 | 1.33 | 0.01 | 1.63 | 0.03 | 1.30 | 0.03 | 1.62 | 0.05 |
| Brain | DC | 44.72 | 4.37 | 41.21 | 2.49 | 42.93 | 1.13 | 37.20 | 1.03 | 49.68 | 2.92 | 39.27 | 2.44 |
| | CD | 0.93 | 0.07 | 1.01 | 0.03 | 0.89 | 0.11 | 0.96 | 0.10 | 0.96 | 0.09 | 1.12 | 0.02 |
| Chest muscle | DC | 58.24 | 4.20 | 51.67 | 3.31 | 57.31 | 4.65 | 49.79 | 7.95 | 55.99 | 2.38 | 38.05 | 6.30 |
| | CD | 1.30 | 0.14 | 1.36 | 0.12 | 1.33 | 0.11 | 1.38 | 0.17 | 1.33 | 0.15 | 1.33 | 0.35 |
| Heart | DC | 55.75 | 1.19 | 48.57 | 2.16 | 55.00 | 1.46 | 45.49 | 0.58 | 54.61 | 2.51 | 41.06 | 0.78 |
| | CD | 1.48 | 0.82 | 1.16 | 0.10 | 1.04 | 0.03 | 1.16 | 0.01 | 1.10 | 0.01 | 1.27 | 0.04 |
| Kidney | DC | 51.93 | 1.35 | 46.73 | 0.90 | 51.27 | 0.93 | 43.24 | 0.43 | 52.01 | 4.14 | 40.97 | 1.48 |
| | CD | 1.10 | 0.03 | 1.16 | 0.01 | 1.05 | 0.01 | 1.14 | 0.04 | 1.09 | 0.05 | 1.22 | 0.11 |
| Leg muscle | DC | 51.19 | 2.65 | 45.94 | 2.16 | 51.54 | 1.33 | 41.98 | 1.84 | 53.43 | 1.59 | 42.06 | 2.10 |
| | CD | 1.36 | 0.05 | 1.38 | 0.09 | 1.33 | 0.07 | 1.31 | 0.07 | 1.47 | 0.06 | 1.48 | 0.06 |
| Liver | DC | 45.33 | 1.21 | 41.26 | 0.72 | 45.21 | 1.57 | 38.49 | 0.84 | 48.97 | 2.10 | 37.42 | 0.95 |
| | CD | 0.93 | 0.01 | 0.95 | 0.01 | 0.94 | 0.02 | 0.97 | 0.02 | 1.01 | 0.04 | 1.10 | 0.05 |
| Lung | DC | 40.15 | 0.37 | 39.15 | 1.33 | 43.28 | 2.42 | 43.09 | 2.10 | 45.15 | 0.38 | 45.21 | 0.51 |
| | CD | 0.88 | 0.02 | 0.86 | 0.03 | 0.99 | 0.05 | 0.98 | 0.04 | 1.01 | 0.01 | 1.00 | 0.01 |
| Pancreas | DC | 53.23 | 3.91 | 49.26 | 3.95 | 51.55 | 7.40 | 45.78 | 4.70 | 49.14 | 2.95 | 42.42 | 1.33 |
| | CD | 1.23 | 0.01 | 1.34 | 0.06 | 1.23 | 0.12 | 1.44 | 0.28 | 1.13 | 0.07 | 1.38 | 0.12 |
| Spleen | DC | 53.55 | 1.36 | 46.61 | 2.17 | 51.75 | 1.19 | 42.45 | 0.70 | 52.90 | 0.70 | 41.63 | 0.70 |
| | CD | 1.11 | 0.01 | 1.19 | 0.01 | 1.14 | 0.03 | 1.29 | 0.03 | 1.08 | 0.01 | 1.29 | 0.04 |

**Table 3.** The dielectric property changes of rat tissues under ultrasound field measured at 2.96 GHz. DC: dielectric constant; CD: conductivity (S/m); SD: standard deviation.

| Tissues | | 67.6 W/cm$^2$ | | | | 120 W/cm$^2$ | | | | 204 W/cm$^2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD |
| Blood | DC | 58.80 | 0.63 | 55.11 | 0.48 | 59.52 | 0.49 | 52.36 | 1.06 | 58.27 | 1.13 | 48.17 | 0.96 |
| | CD | 3.06 | 0.01 | 2.79 | 0.06 | 2.99 | 0.01 | 2.71 | 0.04 | 2.93 | 0.05 | 2.61 | 0.04 |
| Brain | DC | 41.85 | 4.51 | 38.88 | 2.70 | 40.31 | 0.72 | 35.03 | 0.75 | 47.07 | 2.87 | 37.38 | 2.40 |
| | CD | 2.20 | 0.16 | 2.04 | 0.06 | 2.10 | 0.16 | 1.86 | 0.14 | 2.29 | 0.16 | 1.98 | 0.08 |
| Chest muscle | DC | 54.74 | 4.25 | 49.10 | 3.39 | 54.02 | 4.56 | 47.19 | 7.59 | 52.29 | 2.27 | 35.97 | 5.89 |
| | CD | 3.05 | 0.22 | 2.70 | 0.20 | 3.03 | 0.23 | 2.65 | 0.38 | 3.02 | 0.19 | 2.27 | 0.46 |
| Heart | DC | 53.74 | 1.18 | 47.29 | 2.19 | 52.82 | 1.81 | 44.36 | 0.72 | 51.63 | 2.38 | 39.46 | 0.67 |
| | CD | 2.66 | 0.12 | 2.30 | 0.13 | 2.58 | 0.05 | 2.14 | 0.02 | 2.58 | 0.01 | 2.06 | 0.07 |
| Kidney | DC | 49.27 | 1.46 | 44.79 | 1.03 | 48.75 | 1.11 | 41.73 | 0.57 | 49.24 | 4.33 | 39.25 | 1.72 |
| | CD | 2.63 | 0.06 | 2.37 | 0.03 | 2.52 | 0.01 | 2.20 | 0.04 | 2.59 | 0.12 | 2.21 | 0.08 |
| Leg muscle | DC | 47.66 | 2.85 | 43.49 | 2.57 | 48.17 | 1.17 | 39.77 | 1.79 | 49.96 | 1.76 | 39.99 | 1.86 |
| | CD | 2.63 | 0.08 | 2.36 | 0.10 | 2.57 | 0.04 | 2.10 | 0.11 | 2.75 | 0.06 | 2.24 | 0.12 |
| Liver | DC | 41.34 | 1.25 | 38.31 | 0.75 | 41.29 | 1.65 | 36.00 | 0.90 | 45.01 | 2.12 | 35.22 | 0.95 |
| | CD | 2.10 | 0.03 | 1.81 | 0.01 | 2.09 | 0.04 | 1.68 | 0.02 | 2.22 | 0.08 | 1.69 | 0.04 |
| Lung | DC | 37.84 | 0.43 | 36.94 | 1.27 | 40.93 | 2.24 | 40.81 | 1.90 | 42.39 | 0.22 | 42.52 | 0.31 |
| | CD | 1.76 | 0.02 | 1.71 | 0.06 | 1.93 | 0.10 | 1.90 | 0.09 | 2.00 | 0.02 | 1.98 | 0.03 |
| Pancreas | DC | 50.38 | 4.27 | 46.73 | 4.10 | 48.76 | 7.48 | 43.24 | 4.81 | 46.56 | 3.16 | 40.02 | 1.64 |
| | CD | 2.72 | 0.05 | 2.61 | 0.02 | 2.69 | 0.34 | 2.61 | 0.33 | 2.53 | 0.09 | 2.45 | 0.12 |
| Spleen | DC | 51.52 | 1.25 | 45.10 | 2.20 | 49.69 | 1.31 | 41.11 | 0.76 | 50.92 | 0.68 | 40.35 | 0.75 |
| | CD | 2.60 | 0.07 | 2.31 | 0.06 | 2.60 | 0.05 | 2.28 | 0.04 | 2.58 | 0.01 | 2.24 | 0.04 |

**Table 4.** The dielectric property changes of rat tissues under ultrasound field measured at 6.01 GHz. DC: dielectric constant; CD: conductivity (S/m); SD: standard deviation.

| Tissues | | 67.6 W/cm$^2$ | | | | 120 W/cm$^2$ | | | | 204 W/cm$^2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD | Without LIFU | SD | With LIFU | SD |
| Blood | DC | 52.66 | 0.65 | 51.33 | 0.52 | 53.23 | 0.65 | 49.39 | 1.04 | 51.85 | 1.08 | 45.45 | 0.84 |
| | CD | 7.99 | 0.03 | 6.57 | 0.08 | 7.93 | 0.02 | 5.90 | 0.15 | 7.76 | 0.11 | 5.47 | 0.07 |
| Brain | DC | 36.72 | 4.18 | 35.06 | 2.66 | 35.34 | 0.66 | 31.68 | 0.64 | 41.87 | 2.62 | 34.38 | 2.19 |
| | CD | 5.34 | 0.62 | 4.51 | 0.30 | 5.04 | 0.23 | 3.89 | 0.19 | 5.75 | 0.40 | 3.96 | 0.31 |
| Chest muscle | DC | 47.37 | 4.02 | 43.94 | 3.01 | 46.86 | 4.21 | 42.44 | 6.89 | 45.23 | 2.07 | 32.70 | 5.43 |
| | CD | 7.62 | 0.59 | 6.11 | 0.46 | 7.57 | 0.64 | 5.96 | 1.12 | 7.36 | 0.38 | 4.32 | 0.82 |
| Heart | DC | 47.26 | 1.08 | 43.13 | 2.15 | 46.35 | 1.68 | 40.93 | 0.65 | 45.61 | 2.53 | 36.89 | 0.91 |
| | CD | 7.16 | 0.29 | 5.57 | 0.28 | 6.98 | 0.27 | 4.89 | 0.13 | 6.74 | 0.16 | 4.19 | 0.03 |
| Kidney | DC | 42.68 | 1.27 | 40.06 | 0.97 | 42.43 | 1.03 | 37.70 | 0.47 | 42.92 | 4.23 | 35.57 | 2.02 |
| | CD | 6.72 | 0.24 | 5.48 | 0.15 | 6.50 | 0.14 | 4.83 | 0.07 | 6.61 | 0.49 | 4.55 | 0.10 |
| Leg muscle | DC | 42.81 | 2.83 | 40.23 | 2.51 | 43.54 | 0.91 | 37.38 | 1.59 | 45.31 | 1.78 | 37.93 | 1.68 |
| | CD | 6.21 | 0.21 | 5.16 | 0.20 | 6.14 | 0.03 | 4.50 | 0.30 | 6.44 | 0.13 | 4.52 | 0.27 |
| Liver | DC | 36.42 | 1.17 | 35.11 | 0.84 | 36.46 | 1.61 | 33.61 | 0.95 | 39.96 | 1.93 | 33.46 | 0.93 |
| | CD | 5.27 | 0.13 | 4.30 | 0.04 | 5.27 | 0.16 | 3.80 | 0.06 | 5.61 | 0.25 | 3.46 | 0.08 |
| Lung | DC | 34.27 | 0.45 | 33.51 | 1.12 | 37.30 | 1.99 | 37.27 | 1.69 | 38.50 | 0.17 | 38.70 | 0.20 |
| | CD | 4.51 | 0.03 | 4.36 | 0.20 | 4.90 | 0.23 | 4.82 | 0.19 | 5.05 | 0.07 | 5.00 | 0.08 |
| Pancreas | DC | 44.14 | 4.86 | 41.74 | 4.16 | 42.66 | 6.45 | 38.69 | 4.72 | 40.60 | 2.30 | 35.76 | 1.72 |
| | CD | 6.77 | 0.17 | 5.89 | 0.36 | 6.59 | 1.23 | 5.45 | 0.58 | 6.15 | 0.78 | 4.94 | 0.20 |
| Spleen | DC | 45.29 | 1.01 | 40.95 | 1.93 | 43.51 | 1.31 | 37.51 | 0.78 | 44.56 | 0.55 | 36.87 | 0.72 |
| | CD | 6.79 | 0.26 | 5.33 | 0.25 | 6.66 | 0.12 | 4.75 | 0.07 | 6.81 | 0.14 | 4.61 | 0.08 |

The findings from this study can provide a basis that the response of tissue to LIFU modulation can be imaged/monitored by electromagnetic field based imaging techniques such as MTI. In this study, the ultrasound intensity of the LIFU field was selected within the range of safety standards.[43,44] We selected three output voltage gears from small to large on the function generator controlling the transducer, and the specific values of their peak pressures were measured by a hydrophone. These pressure values were similar to those applied to leg neuromuscular stimulation in frogs[45] and hippocampus stimulation in rats.[22] Relevant studies have shown that neuromodulation with LIFU in animals and humans can reversibly inhibit somatosensory evoked potentials.[25,46,47] However, the precise mechanisms of neuromodulation with ultrasound are incompletely understood.[25] This study explains the changes in dielectric properties of biological tissues during neuromodulation by LIFU, which may lead to the inhibition of evoked potentials. One of the leading physical mechanisms of neuromuscular modulation by LIFU is that acoustic tension generated by ultrasound on lipid bilayer may open classical volt-gated ion channels,[48,49] enabling the ions fluidity such as $Na^+$, $K^+$, and $Ca^{2+}$,[50,51] and increasing cell electrical activity to alter membrane conductance.[52] The electrical property measurement results obtained from this study have further verified this hypothesis, and are also consistent with the physics of changed conductivity predicted by the AE Eq. (1).

## 4. Conclusion

This study is the first to measure the frequency-dependent dielectric properties of *in vitro* rat blood, brain, chest muscle, heart, kidney, leg muscle, liver, lung, pancreas, and spleen tissues under varying LIFU field modulations. The dielectric properties can be clearly and directly obtained from Figs. 2–11. Moreover, the data at the four frequencies commonly used for MTI are also clearly shown in Tables 1–4. These data not only offer a fundamental understanding of the changes in tissue electrical characteristics due to AE but also provide a physical reference for MTI and LIFU neuromodulation which depend on changes in the dielectric properties of biological tissues.

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