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Research on Simulation Algorithm of Mechanical and Thermal Indices of Ultrasonic Field Based on LabVIEW

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Abstract. This paper is suitable for the calculation of mechanical and thermal indices in distributed measurement system of ultrasonic field. The cavitation and thermal effect produced by ultrasonic signal acting on human body and the calculation method of mechanical and thermal indices for evaluating these two effects are described. The measurement of acoustic output index of ultrasonic diagnostic equipment can be realized by scanning ultrasonic field. The algorithm is developed based on LabVIEW software and the simulation results can be verified.

1. Introduction

1.1. Distributed Measurement System of Ultrasound Field

The principle of distributed measurement system of ultrasonic field is to control the motion of hydrophone sensor in sound field by mechanical positioning device. The hydrophone receives the acoustic signal from the ultrasonic probe and converts the received ultrasonic signal into voltage signal according to a certain relationship. The received data are collected and modulated by signal acquisition components such as oscilloscope and sent to the upper computer. The collected data are processed by LabVIEW software, the parameters of the ultrasound field are obtained.

1.2. Cavitation Effect

Ultrasound produces an oscillating pressure wave when it propagates through tissues, which causes the formation, growth and size change of microbubbles in tissues. When the intensity and pressure are large enough, these microbubbles break down, which will seriously affect the physiological function and structure of tissues. Mechanical index (MI) is an indicator of cavitation effect and is used to estimate the possibility of cavitation.

1.3. Thermal Effect

Ultrasound beams pass through human tissues, and part of the energy is consumed by absorption, which makes local tissue temperature rise into heat, which is called the thermal effect of ultrasound. In most soft tissues, the rate of energy absorption depends on: tissue attenuation coefficient, the frequency of use, the energy or intensity of ultrasound beam and the exposure time. The tissue with high attenuation coefficient has the strongest thermal effect, such as bone, and the tissue with low attenuation coefficient has the weakest thermal effect, such as amniotic fluid. The World Federation of Medical and Biological Ultrasound (WFUMB; Barnett 1998), based on a review of the study on the effect of fetal temperature rise in animals, concluded that clinical application is harmless when the temperature rise does not exceed 1.5°C, but the potential harm of thermal effect should be considered when the time for



examining embryos and fetuses exceeds 5 minutes and the temperature rise exceeds 4°C. Thermal index (TI) is an indicator of thermal effect, which is used to estimate the possibility of thermal effect.

2. Calculating Method and Simulation

2.1. Calculating Method and Simulation of Mechanical Index (MI)

The mechanical index (MI) is related to the possibility of cavitation. It is defined as the sparse peak pressure (Pr) (negative peak pressure) divided by the square root of the ultrasonic frequency, as shown in formula 1.

$$MI = \frac{p_{r,a} f_{awf}^{-1/2}}{C_{MI}} \quad (1)$$

In formula, $C_{MI} = 1 \text{ MPa MHz}^{-1/2}$, $p_{r,a}$ refers to peak sparse sound pressure after attenuation (MPa), f_{awf} refers to operating frequency of sound (MHz). It should be noted that before determining the mechanical index, the measurement system should first determine the peak sparse sound pressure after attenuation of each point, the index is determined at the position where the maximum attenuation of the pulse sound intensity integral occurs, so the attenuation coefficient must act on the square integral of the pulse sound pressure. In the revised draft of IEC 2002, formula (1) is recommended for the acoustic operating frequency range below 4 MHz, but for the case of $f_{awf} > 4 \text{ MHz}$, the MI should be derived from the following formula 2:

$$MI = \frac{p_{r,a}}{2C_{MI}} \quad (2)$$

Assuming that the attenuated waveform is sinusoidal, we use LabVIEW software to simulate and design a mechanical index (MI) algorithm. The program block diagram is shown in Figure 1.

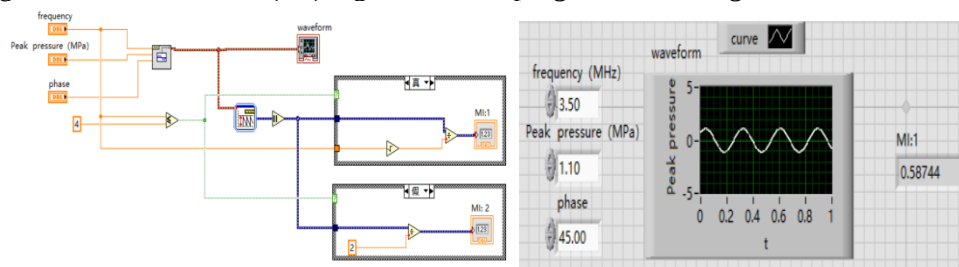


Fig.1 Algorithmic Simulation of Mechanical Index (MI)

2.2. Calculating Method and Simulation of Thermal Index (TI)

TI is the thermal index, which mainly reflects the influence of the thermal effect of ultrasound energy on human tissues. According to the definition of IEC standard, TI is the ratio of the attenuated output power at the designated point to the attenuated output power required to raise the temperature of the point by 1°C under the given tissue model. According to the difference of human tissue model, thermal index (TI) can be divided into TIS, TIB and TIC. TIS is the thermal index of soft tissue, which reflects the temperature rise of non-skeletal tissues including body fluids caused by ultrasound energy absorption. TIB is bone thermal index, which mainly reflects the temperature rise effect of ultrasound energy passing through soft tissue and focusing near the sclerotic skeleton (such as fetal skeleton). TIB is the most suitable index for examining fetus in middle or late pregnancy, during this period, the highest temperature occurring at the interface between soft tissue and skeleton can be detected.

2.2.1. Calculating Method of Thermal Index of Soft Tissue (TIS). The calculation of thermal index (TI) needs to distinguish between scanning mode and non-scanning mode. For each emission pattern in scanning mode, the thermal index of soft tissue should be calculated according to formula 3.

$$TIS = \frac{P_1 f_{awf}}{C_{TIS1}} \quad (3)$$

In formula, $C_{TIS1} = 210 \text{ mW MHz}$, P_1 refers to bounded output power (mW), f_{awf} refers to operating frequency of sound (MHz). For the non-scanning mode, the effective area of the ultrasonic transducer should

be considered firstly. When the output beam area with -12dB meets the requirement of $A_{aprt} < 1.0\text{cm}^2$, the thermal index of soft tissue (TIS) should be calculated according to formula 4.

$$TIS = \frac{P f_{awf}}{C_{TIS1}} \quad (4)$$

In formula, $C_{TIS1} = 210\text{mWMHz}$, P refers to output power (mW), f_{awf} refers to operating frequency of sound (MHz). When $A_{aprt} > 1.0\text{cm}^2$, the thermal index of soft tissue (TIS) should be determined at the depth z , the thermal index of soft tissue should be calculated according to the following formula:

$$TIS = \frac{P_{\alpha} f_{awf}}{C_{TIS1}} \quad (5)$$

Or

$$TIS = \frac{I_{zpta} \cdot \alpha(z) f_{awf}}{C_{TIS2}} \quad (6)$$

Taking the smaller values of the two, in formula, $C_{TIS1} = 210\text{mWMHz}$, $C_{TIS2} = 210\text{mWcm}^{-2}\text{MHz}$, P_{α} refers to attenuated output power (mW), f_{awf} refers to operating frequency of sound (MHz), I_{zpta} , $\alpha(z)$ refers to average sound intensity of spatial peak time after attenuation. According to the above method, LabVIEW can be used to simulate and design the algorithm of TIS, the program block diagram is shown in Fig. 2 and Fig. 3.

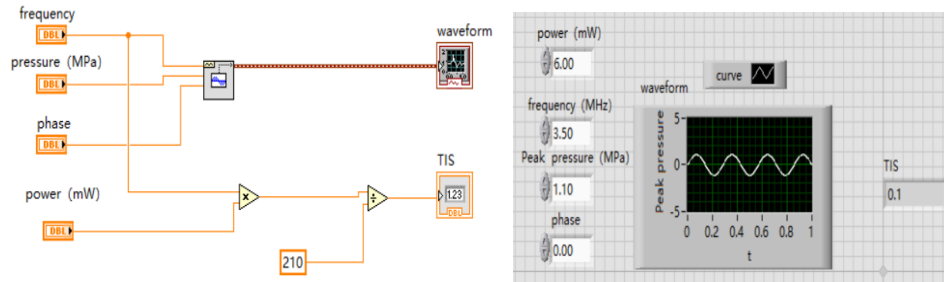


Fig.2 Algorithmic Simulation of TIS under Scanning Mode

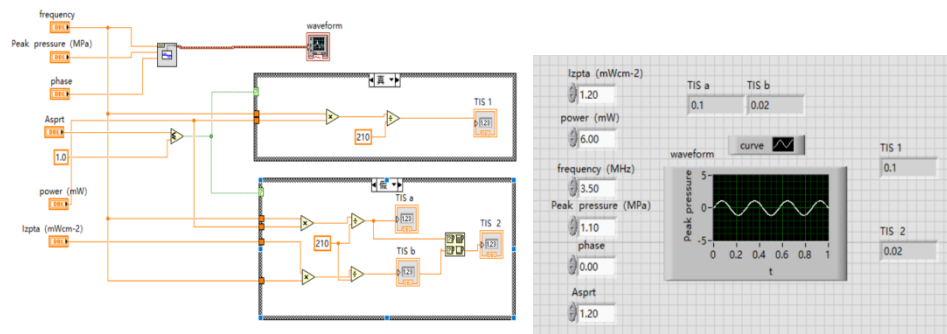


Fig.3 Algorithmic Simulation of TIS under Non-scanning Mode

2.2.2. Calculating Method of Thermal Index of Bone (TIB). The method of confirming TIB in scanning mode should be the same as that method of confirming TIS in scanning mode. For the non-scanning mode, the focus depth of bone tissue (z_b) should be determined firstly, which can be determined by multiplying the distance of the attenuated output power by the variable of the attenuated pulse intensity integral. At the TIB depth z_b , the average sound intensity of attenuated spatial peak time should be calculated according to formula 7.

$$I_{zpta, \alpha(z_b)} = I_{pi, \alpha(z_b)} P_{rr} \quad (7)$$

In formula, $I_{pi, \alpha}$ refers to the integral of pulse sound intensity after attenuation at the TIB depth z_b (mJcm^{-2}), P_{rr} refers to pulse repetition frequency (Hz). For the irradiated bone model near the focal point, the thermal index of bone (TIB) should be calculated according to formula 8.

$$TIB = \frac{\sqrt{P_{\alpha}(z_b) I_{zpta, \alpha}(z_b)}}{C_{TIB1}} \quad (8)$$

Or

$$TIB = \frac{P_{\alpha}(z_b)}{C_{TIB2}} \quad (9)$$

Taking the smaller values of the two, in formula, $C_{TIB1} = 50 \text{ mWcm}^{-1}$, $C_{TIB2} = 4.4 \text{ mW}$, $P_{\alpha}(z_b)$ refers to output power after attenuation at TIB depth $z_b(\text{mW})$, $I_{z_{pta}}$, $\alpha(z_b)$ refers to average acoustic intensity of spatial peak time after attenuation at TIB depth $z_b(\text{mWcm}^{-2})$.

2.2.3. Calculating method of thermal index of skull (TIC). The thermal index of skull (TIC) in scanning mode or non-scanning mode of ultrasound equipment can be obtained from formula 10:

$$TIC = \frac{P/D_{eq}}{C_{TIC}} \quad (10)$$

In formula, $C_{TIC} = 40 \text{ mW/cm}$, P refers to acoustic output power (mW), D_{eq} refers to equivalent aperture diameter (cm), which equates the -12 dB output beam area to a standard circle, and D_{eq} is the diameter of the circle. Namely:

$$D_{eq} = \sqrt{\frac{4}{\pi} A_{aprt}} \quad (11)$$

According to the above methods, the algorithms of thermal index of bone (TIB) and thermal index of skull (TIC) under non-scanning mode are designed. The program block diagram is shown in Fig.4.

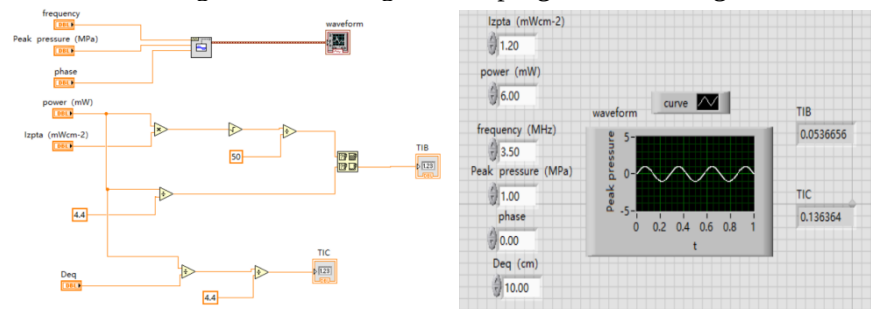


Fig.4 Algorithmic Simulation of Thermal Index of Bone (TIB) under Non-scanning Mode and Thermal Index of Skull (TIC)

3. Result Analysis

A qualified milliwatt-level ultrasonic power meter and a calibrated hydrophone are selected to measure the output sound field of a medical ultrasonic diagnostic equipment. The measurement results are recorded, the mechanical index and thermal index are calculated using the simulation algorithm. The results are compared with the display values of the ultrasonic equipment. The measurement process is shown in Fig.5. Probe of B-mode ultrasound is a common convex array probe, with a frequency of 3.5 MHz, a mechanical index (MI) of 0.6 and a thermal index (TIS) of 0.1. The results of measurement are as follows: negative peak pressure $P_{ra} = 1.099 \text{ MPa}$, $p = 40 \text{ mW}$, the scanning width of probe is 5 cm, bounded output power $P_1 = 5 \text{ mW}$, the measured results are input into the simulation algorithm and the measured results are shown in Fig.6, $MI = 0.587$, $TIS = 0.133$, which are very close to the display value of ultrasound equipment, and the reliability of the algorithm is verified. It can be used in distributed ultrasonic field measurement system to realize the real-time calculation of these two indices.



Fig.5 Measurement of Sound Field by Ultrasonic Power Meter

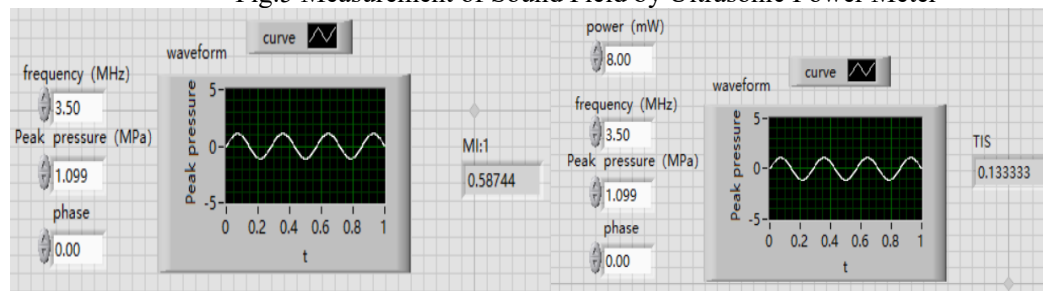


Fig.6 Simulation Result

4. Conclusion

The application of diagnostic ultrasound in medicine is expected to achieve accurate and good diagnostic and therapeutic effects, but the premise is to ensure the patient's medical safety. In order to obtain the expected results which are harmless to human body, ultrasound users must always pay attention to the real-time MI and TI values displayed on the screen of ultrasound equipment. MI and TI are not absolute values, but a rough way to produce biological effects. It is estimated that the higher the index is, the greater harm will be. Therefore, it is very important to realize the traceability of the two indexes and ensure their accuracy. In practical clinical application, equipment users should also follow the principle of ALARA (As low as Reasonable Achievable), that is, they should always pay attention to MI and TI values without affecting the access to necessary diagnostic information, so as to minimize the potential hazards to patients.

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