Study of the effect of ultrasound scanner settings on the level of radiation intensity by the reciprocity method

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Abstract. In this paper, a new method of measuring the intensity on the radiating surface of the convex sensor of the ultrasonic diagnostic scanner EDAN U50 with its various settings was proposed, based on the reciprocity method using a hydrophone calibrated with a vibration simulator. The effect of the following scanner settings on the peak-spatial average time-averaged intensity in B-mode was experimentally investigated: ultrasonic radiation frequencies, number of focuses, and number of focus positions. It was found that changing the scanner settings significantly changes the temporal parameters of the emitted bursts of pulses, which affects the result of averaging intensity over time. At the same time, an increase in the number of focuses leads to a decrease in intensity, while an increase in the focus of the positions and frequency of the radiation, on the contrary, leads to its growth. Studies have shown that the intensity value exceeds the allowable values at almost any settings of the ultrasound scanner, with the exception of the ultrasound frequency of 2.5 MHz.

1. Introduction

The traditional use of ultrasound in medicine is primarily associated with diagnosis (visualization of internal organs). Ultrasound (US) methods are among the most common in medical diagnostics. Intensive development of new ultrasound diagnostics methods over the past 20 years, the creation of more and more complex instruments and systems that implement these methods required the development and standardization of new methods for an objective assessment of their consumer properties and their safe use parameters [1-3]. Increasing the intensity level of ultrasonic radiation in diagnostic devices and systems improves image visualization, but the safe use of medical diagnostic ultrasound is limited by its dosage. High levels of ultrasonic radiation intensity can lead to undesirable consequences due to thermal and mechanical effects of ultrasonic vibrations (acoustic cavitation, accompanied by mechanical destruction of cells, overheating of biological structures, etc.) [4]. Therefore, the issues of safety assessment of ultrasonic diagnostics devices, their certification and periodic calibration are topical.

International standards and their domestic counterparts regarding the safety of the use of devices and devices for ultrasound therapy and diagnostics [GOST R 50.2.051-2006. Ultrasonic diagnostic equipment for medical purposes. General requirements for control methods of technical characteristics; GOST IEC 61157-2013 GSI Medical electrical equipment. Devices for ultrasonic diagnostics. Requirements for the declaration of acoustic output parameters in technical documents;
GOST IEC 61161-2014. Ultrasonic power in liquids. General requirements to measuring methods in the frequency range 0.5 to 25 MHz; GOST IEC 62127-1-2015. Parameters of ultrasonic fields. General requirements to measuring methods and characterization of fields in the frequency range 0.5 to 40 MHz. It is regulated that the manufacturer of the equipment declares in the technical documentation for the product such acoustic parameters as the full power of the ultrasonic beam, peak values of intensity and acoustic pressure, and so on.

The requirements for the parameters of ultrasonic medical equipment for various purposes and their measurement methods, practical problems of assessing its technical condition during its operation have been considered previously, mainly in relation to ultrasound therapy devices, surgery, lithotripsy, ultrasound modes of which are especially dangerous for the human body [4-6]. Methods for estimating the intensity of ultrasound radiation based on measuring radiation pressure forces using targets according to GOST R 8.583-2001 [GOST R 8.583-2001 (IEC 61689-96) Medical ultrasonic therapeutic equipment. General requirements for measurement procedures of the acoustic output performance in the frequency range from 0.5 MHz to 5.0 MHz] are used for calibration of this kind of ultrasonic medical equipment. These methods are applicable mainly to the low-frequency region and do not have sufficient sensitivity to high-frequency low-intensity and, especially, to diagnostic pulsed radiation. In the literature there is information about the possibility of using as a target a set of gas bubbles in a liquid [7], or soft spherical scatterers for assessing the intensity of diagnostic ultrasound radiation [8-9].

The international standard [GOST IEC 61157-2013 GSI Medical electrical equipment. Devices for ultrasonic diagnostics. Requirements for the declaration of acoustic output parameters in technical documents] for measuring acoustic parameters of diagnostic ultrasound recommends the use of the reciprocity method using specially designed calibrated hydrophones placed at the studied point in space with an intensity maximum, as a rule, by foreign manufacturers.

The technical capabilities of ultrasound scanners, which are expanding every year, are being provided with an increasing number of adjustable parameters. Any ultrasound diagnostic equipment, in which there is a possibility of complete programmed control of the acoustic output level, should switch to the appropriate factory default settings, which can later be reconfigured by the doctor for the patient to improve visualization. The ultrasound doctor’s adjustment of the scanner settings to achieve a better picture in the process of diagnostics can lead to an unpredictable change in the level of the radiated acoustic power.

The article presents the results of experimental studies of the effect of the ultrasonic ultrasound scanner EDAN U50 settings on the ultrasound intensity measured by the reciprocity method on the ultrasonic surface of a convex sensor using a hydrophone calibrated with a vibration velocity simulator.

2. Approaches used
According to the recommendations of the International Electrotechnical Commission (IEC), many parameters of ultrasonic diagnostic transducer are determined to determine the safety of ultrasonic radiation, the main of which are: time-averaged output power $I_{ob}$; peak acoustic vacuum pressure $p$; peak-spatial time-averaged $I_{spa}$ intensity.

According to GOST IEC 61157-2013, for all operating modes of the device for the specific combination of sensor and electronic unit of the ultrasonic device, the maximum possible levels are regulated: for $I_{ob} < 20$ mW / cm$^2$, for $p < 1$ MPa, for $I_{spa} < 100$ mW / cm$^2$.

The study of the effect of the settings on the intensity level was carried out on the universal portable ultrasound scanner EDAN U50, used in all areas of ultrasound diagnostics. The main technical characteristics of the scanner, including the ranges of adjustable parameters are presented in Table 1.
Table 1. Technical characteristics, main modes and functions of the ultrasound scanner EDAN U50.

| Visualization modes                                                                 | B, B / B, 4B, B / M, M, PD, PW, CDF, THI, TSI tissue harmonic, directional power doppler, tissue doppler, pulse wave doppler, etc. |
|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| Types of sensors                                                                    | Convex, linear                                                                                                                   |
| Operating frequency                                                                 | Linear sensor — 4.5/ 5.5/ 6.5/ H5.6/ H6.0 MHz; Convex sensor — 2.5/3.5/4.5/ H2.5/H2.7 MHz |
| Scandepth                                                                           | From 20 to 250 mm                                                                                                               |
| The number of focuses                                                               | 1, 2, 3, 4                                                                                                                       |
| The number of focus positions                                                       | 1, 7, 15                                                                                                                         |
| Segment regulation of acoustic output power                                         | There is                                                                                                                         |

Studies of the effect of ultrasound scanner settings on the level of radiation intensity were carried out for a B-mode convex sensor of an EDAN U50 medical scanner by varying the following settings: ultrasound frequency — 2.5 MHz, 3.5 MHz and 4.5 MHz; the number of focuses — 1, 2, 3, 4, the number of focus positions — 0, 7, 15.

For measuring the intensity of ultrasonic radiation, the reciprocity method was used, based on receiving signals from the radiating surface of an ultrasonic sensor of a diagnostic scanner in the B-mode of visualization using a point probe hydrophone according to the functional diagram in Figure 1.

Figure 1. Block diagram of the measurement of the intensity of ultrasound radiation.

The design of the hydrophone includes a sensitive element (piezoplates TTS-19 with a thickness of \( d_{\text{pp}} = 0.67 \) mm and linear dimensions of 2 \( \times 2 \) mm), a protector, a damper and a shielded case. The hydrophone is calibrated for sensitivity over a wide frequency range using a specially designed vibration velocity simulator (Fig. 2). The principle of operation of the vibration velocity simulator consists in the appearance of oscillations of an inductor with alternating current, which is in the field of a permanent magnet, due to the Ampere force \( F_A \). Through a layer of glue, the oscillations of the inductor are transmitted to the prism from plexiglass, and are removed through a contact liquid using a calibrated hydrophone.

The value of vibration velocity \( V_{\text{in}} \) ultrasonic vibrations emitted by the simulator is determined by the formula:

\[
V_{\text{in}} = \frac{F_A}{m\omega} \cdot \Delta \cdot K_\delta \cdot K_R = \frac{inBl}{m\omega} \cdot \Delta \cdot K_\delta \cdot K_R
\]  

(1)

where \( B \) - is the induction of a constant magnetic field, \( i \) — is the current in the inductor, \( l \) - is the length of the inductor in a magnetic field, \( m \) - is the mass of the inductor, \( n \) - is the number of turns of the inductor, \( \omega \) - is the cyclic frequency of the oscillations, \( \Delta, K_\delta, K_R \) — is the correction the coefficients on
the damping of the oscillations of the inductor from the side of the Plexiglas, on the attenuation of the ultrasonic wave in the Plexiglas, on the divergence of the ultrasonic wave due to the formation of the radiation pattern (calculated theoretically).

In particular, in a magnetic field with induction \( B = 0.4 \) T with a current in the inductor \( i = 4.5 \) A, with the linear size of the inductor \( l = 12 \) mm, the mass of the inductor \( m = 6.8 \) \( \mu \)g, the number of turns of the inductor \( n = 10 \) the Ampere force is estimated by the value \( F_A = 0.22 \) N, which corresponds at the frequency of 1 MHz to the value of the vibration velocity \( V_{im} = 10 \) \( \mu \)m / s and the intensity \( I_{im} = 10^{-5} \) mW / cm\(^2\). The amplitude-frequency characteristic of the simulator vibration velocity is shown in Fig. 3, a. A feature of the proposed simulator is a fairly uniform non-resonant amplitude-frequency characteristic due to the lack of dependence of the Ampere force on the frequency.

Figure 2. The principle of the vibration velocity simulator (a), the appearance of the vibration velocity simulator (b).

Figure 3. Amplitude-frequency characteristic of the simulator of vibration velocity (a), calibrated hydrophone (b).

Calibration of ultrasonic hydrophone is performed according to the scheme shown in Figure 4. The simulated vibration velocity is supplied from the generator with a fixed voltage of a given frequency.

The signal converted from electrical to acoustic in the simulator vibration velocity is transmitted to the hydrophone through a layer of contact fluid. The electrical signal from the output of the hydrophone is amplified by a resonant amplifier with a known frequency response and is recorded on an oscilloscope. Measuring the value of the electrical voltage \( U \), corresponding to the known calculated value of vibration velocity \( V_{im} \) or intensity \( I_{im} \), allows determining the sensitivity of a
hydrophone by vibration velocity \( S_y = \frac{U}{V_{im}} \) and intensity \( S_I = \frac{U^2}{I_{im}} \) in a wide frequency range. Figure 3b shows the results of the ultrasound receiver calibration by the vibration speed \( S_v \) and the intensity level \( S_I \) in the frequency range from 0.8 MHz to 10 MHz. In particular, according to Fig. 3, the sensitivity of a hydrophone at a frequency of \( f = 2.5 \) MHz \( S_I = 3 \cdot 10^{-4} \) V² / (W/cm²), at a frequency of \( f = 3.5 \) MHz \( S_I = 1 \cdot 10^{-4} \) V² / (W/cm²), at the frequency \( f = 4.5 \) MHz \( S_I = 0.3 \cdot 10^{-5} \) V² / (W/cm²).

**Figure 4.** The block diagram of the calibration of the receiver ultrasonic vibrations using the simulator vibration velocity.

The type of time sweeps of the signal received by the hydrophone from the surface of the ultrasonic scanner sensor at different time scales is presented in Figure 5.

**Figure 5.** Type of timebase of the received signal.

According to the definition, spatial peak of time-averaged intensity (spatial-peak temporal-average intensity) \( I_{SPTA} \) is the maximum value of time-averaged intensity in an acoustic field or a specific plane. According to the time sweeps of Fig. 5, the peak-spatial time-averaged intensity is determined by the formula

\[
I_{SPTA} = 6U^2 \tau \tau_p / S_I T_r T_{pps}
\]  

(2)

where \( U \) – is the amplitude of the pulse, \( V \), \( \tau \) – is the duration of a single pulse, \( \mu s \), \( T_r \) – is the pulse repetition period in the radiated wave packet of pulses, \( \mu s \), \( \tau_p \) – is the wave pulse duration, \( \mu s \), \( T_{pps} \) is...
the pulse repetition period for one scanning line, ms, $S_i$ – sensitivity of a point hydrophone at a given frequency, $V^2/(W/cm^2)$.

3. Results and discussion

The results of the influence of the number of focuses and the number of focus positions in various frequency ranges on the intensity value are presented in Fig.6. It was experimentally found that changing the scanner settings significantly changes the temporal parameters of the emitted wave packets of pulses, which affects the result of the averaging of the intensity over time, and therefore the intensity value of the $I_{SPTA}$.

The number of foci affects the shape of the ultrasound beam within the set scanning depth. One focus forms a highly focused beam within a small area along the beam. An increase in the number of focuses leads to the formation of a narrower zone of the ultrasonic beam narrowed in depth, while the focusing coefficient decreases. An increase in the number of focuses leads to an increase in the duration of the wave packet of pulses in the time scan due to an increase in the pulse repetition period in the emitted wave packet, which leads to a decrease in $I_{SPTA}$ intensity.

Increasing the number of focus positions shifts the focus area (focus zone) to a depth within the established depth of view, and leads to an increase in the duration of the wave packet of pulses in the time scan due to an increase in the pulse repetition period and the number of pulses in the emitted wave packet, which leads to an increase in $I_{SPTA}$ intensity.

There is a fairly stable dependence of the increase in intensity at high frequencies, with a decrease in the number of focuses and an increase in the number of focus positions.

![Figure 6](image_url)

**Figure 6.** The results of measuring the intensity of $I_{SPTA}$ on the surface of the ultrasonic scanner convex sensor.

Studies have shown that the $I_{SPTA}$ intensity value exceeds the maximum possible levels (100 mW / cm$^2$) in almost any settings of the ultrasound scanner, except for using the 2.5 MHz frequency.

4. Conclusion

Thus, changing the scanner settings during the research process can lead to a significant increase in the intensity of ultrasound radiation, which can cause thermal and mechanical effects associated with the safety of ultrasound diagnostics. At the same time, an increase in the frequency of ultrasonic radiation leads to a significant increase in intensity and its excess of the maximum permissible value of 100 mW / cm$^2$ according to GOST IEC 61157:2013 with all possible variations of the scanner settings, which must be taken into account in the research process, especially the subsurface organs. Focus positions allow you to change the position of the focus in the scanning zone, which allows you to improve the resolution in the area being investigated, but an increase in this parameter leads to an increase in the duration of the wave packet of pulses in the time scan and, consequently, to an increase in intensity.
and this pattern is observed for all radiation frequencies and the number of focuses. An increase in the number of focuses leads to an increase in the duration of the wave packet of pulses in the time scan due to an increase in the pulse repetition period in the emitted wave packet, which leads to a decrease in intensity. Therefore, in the process of conducting a diagnostic study, the physician should be careful to change the settings of the ultrasound scanner in order to avoid negative consequences and use the lowest possible frequencies of ultrasound radiation, focus positions and other parameters. It should be noted that the intensity in the volume of the irradiated medium may be significantly higher in comparison with that measured on the sensor surface, due to focusing effects.

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