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Ultrasonic Method of Blood Flow Velocity Determination: Physical Bases and Vector Visualization

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In the work, the mechanisms of the influence of ultrasound waves on biological tissues from the point of view of visualization of pathological processes in them and blood flow speed estimation of based on the Doppler effect were studied. It was established that the reflection and absorption of ultrasound by tissues depends on their structure, properties, and frequency of ultrasonic oscillations. The ultrasound absorption coefficient changes significantly when the structure and state of the tissue changes due to the development of a pathological process in it. Ultrasound in the therapeutic effect on tissue causes mechanical, thermal and physical and chemical effects, the ratio between which depends on the intensity of action and external conditions. On the basis of sonograms obtained in ultrasound devices using the Doppler effect, an assessment of the blood flow rate in the vessels of various organs and benign tumors was carried out. It is shown that in large vessels, the speed of erythrocytes varies depending on their location relative to the central axis. The ultrasound wave is reflected from different erythrocytes, so the Doppler shift is a frequency interval. This method allows you to quantitatively measure the average linear speed of blood flow.

Keywords: Ultrasound diagnostics (USD), Doppler effect, Sonograms, Blood flow velocity.

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1. INTRODUCTION

Modern ultrasonic and laser technologies based on piezo- and strainresistive and optical effects are widely used in sensor technology and medical equipment (see, for example, [1-3]).

Ultrasound diagnostics (USD) is a method in which ultrasonic waves are used to obtain an image of the internal organs and vessels of the human body. The method is based on the registration of ultrasonic waves reflected from biological objects. Such a diagnostic technique is characterized by high accuracy, simplicity, no radiation exposure, non-invasiveness, the possibility of multiple examinations, and real-time mode.

In medical practice, ultrasonic vibrations with a frequency from 800 to 3000 kHz are used. The absorption of ultrasound by pathological tissues depends on their acoustic properties and the frequency of ultrasonic vibrations. The intensity of ultrasound with a frequency of 800-900 kHz is reduced by approximately half in soft tissues at a depth of 4-5 cm, and at a frequency of about 3000 kHz - at a depth of 1.5-2 cm. Fat tissue absorbs ultrasound approximately 4 times, muscle – 10 times, and bone – 75 times stronger than blood. The strongest absorption of ultrasound is observed at the border of tissues that have different acoustic properties (skin – subcutaneous tissue, fascia - muscle, periosteum – bone). Absorption of ultrasound noticeably changes when the condition of the tissue changes due to the development of a pathological process in it (edema, infiltration, fibrosis, etc.). The speed of ultrasound propagation is maximal in solid media, minimal in gaseous media.

The basis of the physiological and therapeutic effect of ultrasound is the mechanical, thermal, and physicochemical effects caused by it, the ratio between which depends on the intensity of the effect and the conditions of its implementation [4]. An important role is played by the neuro-reflex mechanism of influence on the body.

With focused transmission, both one beam and several parallel beams can be generated (Fig. 1). Although each generated image is affected by low contrast and spatial resolution, a significant improvement in quality can be achieved by coherently compositing multiple plane wave images while maintaining a frame rate 10 to 15 times higher than standard acquisition.

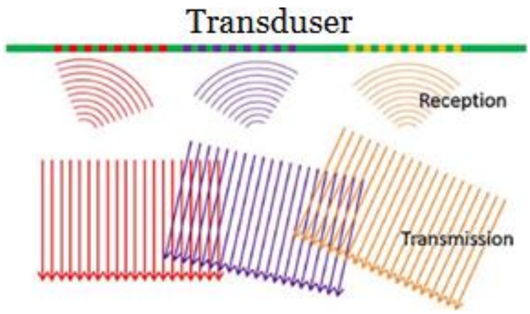


Fig. 1 – Scheme of multidirectional transmission and reception of signals of the scanning sequence, which is used in the vector image of the flow based on the visualization of a plane wave

The ratios of the frequency and depth of ultrasound penetration in the soft tissues of the body are approximately: 1 MHz – up to 50 cm; 3.5 MHz – 30 cm; 5 MHz – 15 cm 7.5 MHz – 7 cm 10 MHz – 5 cm.

The ultrasonic research method also makes it possible to characterize the flows in the vessels. This ability is based on the Doppler effect, which is observed due to the fact that the speed of propagation of ultrasound in any homogeneous medium is constant. By comparing the original frequency of ultrasound with the modified one, it is possible to determine the Doppler shift and estimate the speed [4, 5].

Doppler modes allow you to evaluate the main parameters of blood flow – speed, direction, laminarity, as well as the degree of vascularization of the area under study. Currently, the following types of Doppler studies are used in clinical practice: continuous and pulsed stream spectral Doppler, color Doppler mapping, power Doppler, convergent color Doppler.

Physical and chemical action of ultrasound is characterized by mechanical resonance, under the influence of which the circulation of molecules accelerates, their decay into ions increases, the isoelectric state changes, new electric fields are established, and radicals in retail biochemical products appear. Ultrasound stimulates tissue digestion and oxidation processes in tissues, influencing carbohydrate, fat and mineral metabolism.

The flow of molecules through the clitin membrane is described by Fick's first law:

$$\vec{j} = -D\frac{dc}{dx},$$

where D is diffusion coefficient; dc/dx is substance concentration gradient.

$$\vec{j} = -D\frac{c_{1l} - c_1}{l} = P(c_1 - c_{1l}),$$

where $P = D / l$ is membrane permeability coefficient; l is membrane thickness.

The flow through the membrane is described by equation

$$\vec{j}_{eff} = \frac{D_{eff}}{l_{eff}}\left(c_1 - c_{l1}\right) = P_{eff}\left(c_1 - c_2\right),$$

where D_{eff} is generalized diffusion coefficient; P_{eff} is permeability; c_1 and c_2 is concentration of molecules.

Under the influence of ultrasound, the magnitude Δx_1 and Δx_2 are significantly reduced as a result of intensive mixing of the solution by microflows. The flow of substances through the membrane increases [5, 6].

Absorption of ultrasound by tissues depends on their acoustic properties and the frequency of ultrasound vibrations. The strongest absorption of ultrasound is observed at the border of tissues that have different acoustic properties. Absorption of ultrasound noticeably changes when the state of the tissue changes due to the development of a pathological process in it.

The work purpose was to study the mechanisms of the influence of ultrasound waves on biological tissues from the point of view of pathological processes visualization and the estimation of blood flow speed based on the Doppler effect.

2. METHODS AND RESULTS

Diagnostic Ultrasound System DC-N3 PRO/DC-N3T/DC-N3 with high image quality and color doppler was used to visualize changes in biological tissues using the ultrasound method. The device works in dynamic mode (range 180 dB) and has automatic image optimization. Scanning takes place in two-dimensional and triplex modes using linear multi-frequency sensors; scanning depth up to 30 cm (Fig. 2). Zooming in on a real-time scale; automatic analysis of Doppler curves is performed.

The main characteristics of ultrasonic waves are the period of oscillation (T) – the time during which a molecule or particle of a substance makes one complete oscillation, frequency (ν) – the number of oscillations per unit of time, length (λ) – the distance between the points of one phase and the speed of propagation (s), which depends on the elasticity and density of the medium. The length of the wave is inversely proportional to its frequency.

Color Doppler mapping (Color Doppler) is based on encoding in color the value of the Doppler shift of the emitted frequency. The technique provides direct visualization of blood flows in the heart and in relatively large vessels, and allows obtaining real-time two-dimensional information about blood flows in addition to conventional two-dimensional visualization.

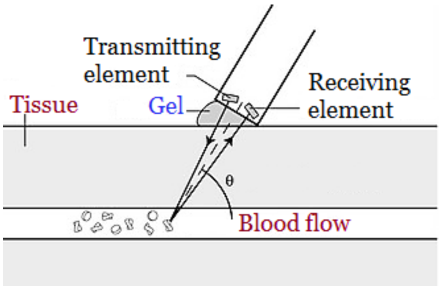
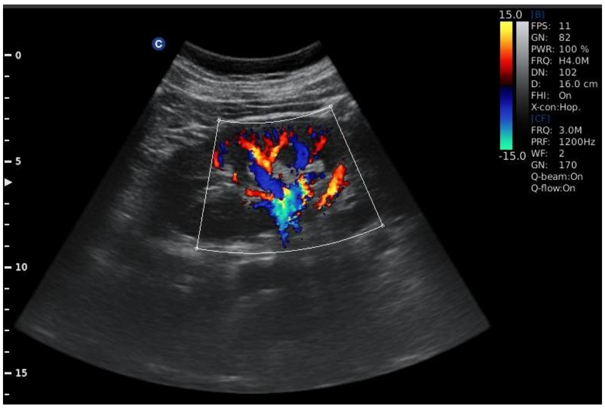
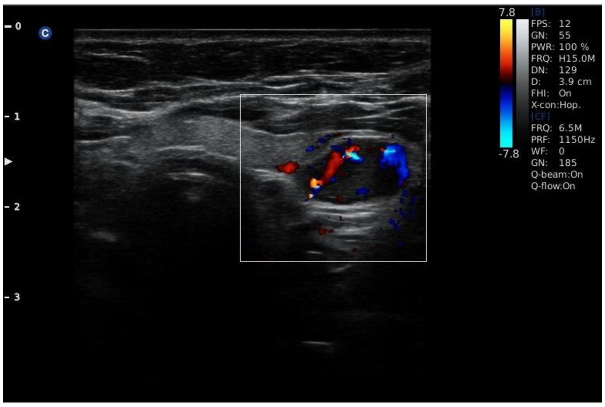


Fig. 2 – The scheme of ultrasound wave propagation when generated by its source



a



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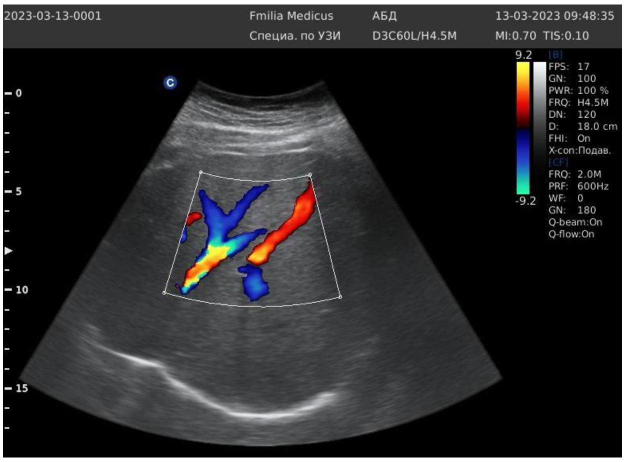

c

Fig. 3 – Examples of sonograms: a – sonogram from the kidney, visualized blood movement (red is the movement of blood from the sensor, and blue – to the sensor); b – a node in the thyroid gland, the peripheral type of blood circulation around the node is determined, a sign of a benign process; c – liver vessels using different types of Doppler effect. color and energy Doppler, respectively

If the reflected signal has a frequency different from the emitted one, then this means that it was reflected from a moving object. Typically, the direction of flow towards the sensor is coded in red and away from the sensor in blue. The brightness of the color is determined by the flow rate. Dark shades of these colors correspond to low speeds, light shades to high ones [7].

In large vessels, the speed of erythrocytes varies depending on their location relative to the axis: "paraaxial" erythrocytes move at a higher speed, and "parietal" erythrocytes move at a lower speed. The ultrasound wave is reflected from different erythrocytes, so the Doppler shift is a frequency interval. This method allows you to quantitatively measure the average speed of blood flow.

In order to estimate the velocity of blood flow by the Doppler frequency shift, it is necessary to approximately measure the angle of inclination of the sensor and take into account that the maximum value of the Doppler shift will be observed at the angle of inclination $\alpha = (30\text{-}45)°$ [7].

Fig. 3 shows examples of sonograms that visualize changes in tissues under the influence of focused ultrasound radiation in two-dimensional mode (mode B) and using the effect of color Doppler mapping (mode D).

On the basis of sonograms, an assessment of the blood flow velocity of benign neoplasms of the breast and thyroid glands, as well as the vessels of the kidney and liver was carried out, the following results were obtained: the velocity of blood flow in the arteries of fibroadenoma from 0.6 cm/sec to 3.0 cm/sec (average value = 2.3 cm/sec); the speed of blood flow in the kidney is 50-125 cm/s; in the liver 11.2-15.5 cm/s; in various areas of the vascular network of the thyroid tissue, it practically does not differ from the speed in the upper and lower thyroid arteries and is about 0.18-0.20 cm/s. It has been proven that the method of color Doppler mapping in the diagnosis of neoplasms gives a completely reliable result in the case of benign neoplasms.

CONCLUSIONS

1. Mechanisms of influence of ultrasonic waves on biological tissues from the point of view of visualization of pathological processes were studied.
2. It was established that the ultrasound absorption coefficient changes significantly when the structure and state of the tissue changes due to the development of a pathological process in it.
3. On the basis of sonograms, an assessment of the speed of blood flow in the vessels of various organs and benign tumors was carried out.
4. It has been proven that the method of color doppler mapping in the diagnosis of neoplasms gives a completely reliable result in the case of benign neoplasms.

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Ультразвуковий метод визначення швидкості кровотоку: фізичні основи та векторна візуалізація

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У роботі вивчені механізми впливу ультразвукових хвиль на біологічні тканини з точки зору візуалізації патологічних процесів в них та оцінці швидкості кровоплину на основі ефекту Допплера. Установлено, що відбиття і поглинання ультразвуку тканинами залежить від їх структури, властивостей і частоти ультразвукових коливань. Коефіцієнт поглинання ультразвуку суттєво змінюється при зміні структури і стану тканини в зв'язку з розвитком в ній патологічного процесу. Ультразвук при терапевтичному впливі на тканину викликає механічний, тепловий і фізико-хімічний ефекти, співвідношення між якими залежить від інтенсивності дії та зовнішніх умов. На основі сонограм, отриманих в ультразвукових апаратах з використанням ефекту Допплера, проведена оцінка швидкості кровоплину в судинах різних органів та доброякісних пухлинах. Показано, що у великих судинах швидкість еритроцитів різна залежно від їх розташування відносно центральної осі. Ультразвукова хвиля відбивається від різних еритроцитів, тобто допплерівське зміщення - це інтервал частот. Даний метод дозволяє зробити доволі точну оцінку середньої лінійної швидкості кровоплину.

Ключові слова: Ультразвукова діагностика (УЗД), Ефект Доппдера, Сонограми, Швидкість кровоплину.