Bioacoustic range equation

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In order to describe and analyze the bioacoustic link, the authors of this study used a modified range explicit equation formulated for a hydroacoustic link. The equation makes it possible to design a bioacoustic link by assuming a given study range in a biological medium, and estimating the required power ratio or power level drop, and then selecting a value for the ratio by means of ultrasonic transducer parameters. A biological medium submerged in water between a transmitting and receiving ultrasonic transducer was studied in a streamlined manner as quasi-homogeneous, or more specifically, in the form of a multilayered tissue structure with parallel border surfaces. In the paper, sample calculations of the relation between power level drop and the length of the bioacoustic link in biological media, for ultrasonic wave frequency in the range of 1 – 5 MHz were performed; using a modified range explicit equation formulated for a hydroacoustic link. The calculations were verified in an experiment.

Keywords: bioacoustic link, hydroacoustic link, range equation, biological media

1. Introduction

A transmission system consisting of two ultrasonic transducers, one of which is the transmitter and the other is the receiver, can be called an ultrasonic link. If water with the biological structure submerged in it, or the biological structure itself, is the medium in such a system, it can be described as a bioacoustic link. The range of the link is defined as the greatest distance between the transmitting and receiving transducer that allows the transmission of the ultrasonic signal. Thus, the range of a bioacoustic link depends on the parameters of ultrasonic transducers (size, operating frequency, directivity characteristics, supply voltage, the effectiveness of the transmitting transducer, the sensitivity of the receiving transducer, noise amplitude, and noise in a receiver circuit); as well as the parameters of water and biological medium (temperature, speed of propagation and attenuation of the ultrasonic wave, the coefficients of ultrasonic wave transfer at the borders of heterogeneity).

Hydroacoustic systems are designed using the range equation formulated by Urick [1]. The equation for the communication link, including the spherical shape of the wave front and the attenuation in the medium, can be presented in the implicit form:

$$20\log\left(\frac{r}{r_S}\right)+2\alpha_f\cdot(r-r_S)=SL-NL-DT=10\log\left(\frac{I_T(r_S)}{I_o}\right)-10\log\left(\frac{I_N}{I_o}\right)-10\log\left(\frac{I_N}{I_R}\right), \quad (1)$$

where α_f – pressure attenuation coefficient of ultrasound in water for the frequency of f, r_S – the distance at the transmitter surface for which the intensity of generated ultrasonic wave I_T is determined, r – link length, SL – source level, NL – noise level, DT – detection threshold, I_N – the equivalent electric and acoustic noise intensity at the link, I_R – acoustic intensity on the surface of the receiving transducer. The reference intensity at the hydroacoustic link $I_o = 0.67\cdot10^{-18}$ W/m^2 results from the reference acoustic pressure, usually assumed as $\tilde{p}_o = 1$ μPa. Taking into account the attenuation in equation (1) makes it impossible to provide the range as a function of parameters of the range equation in the analytical form. This equation requires the use of numerical methods.

The explicit universal range equation formulated for a hydroacoustic link is much better suited to describe and analyze a bioacoustic link [2]:

$$\frac{P_T}{P_R}=K_A d^2 e^{\mu d}, \quad (2)$$

where: P_T – acoustic power radiated by the transmitting transducer, P_R – acoustic power received by the receiving transducer, $\mu = 2\alpha$ – the energetic coefficient of attenuation for an ultrasonic wave, d – link length (the distance between the transmitting and receiving transducer). K_A is a constant defined as the directivity of the transmitting transducer, and is expressed by the formula:

$$K_A=\frac{4\pi}{\Omega_T\cdot S_R}, \quad (3)$$

where Ω_T – the directivity coefficient of the transmitting transducer, S_R – the effective surface of the receiving transducer. Equation (2) enables one to design a bioacoustic link by providing a specific range d for a study in a biological medium, and estimating the required acoustic power ratio P_T/P_R or the decrease in the acoustic power level $L_{P_T/P_R}=10\log(P_T/P_R)$, taking into account all factors having the most significant effect on the speed and attenuation of sound in a biological medium, and then selecting the values of this ratio using the parameters of ultrasonic transducers.

Research related to the analysis of ultrasonic wave transmission in floating gas media that has been carried out by the authors, and which resulted in the development of a computer model of an ultrasonic link for air in static and flow conditions [3-9], enabled, among other options, the development of several forms of aeroacoustic link range equations based on the formula (2). These equations can be also adapted in order to determine the range of a bioacoustic link, which is the subject of this paper.

2. Bioacoustic link range equation

The bioacoustic link can be simulated numerically using a complex mathematical model describing the propagation of a three-dimensional acoustic wave of finite amplitude, based on the modification of a nonlinear KZK equation [10-13]. Such a model applies to both near-field and far-field, and takes into account the effect of linear and nonlinear phenomena. However, it requires the use of sophisticated numerical models and the development of specialized computational software tools.

Another, less complicated way to simulate the bioacoustic link can be numerical modeling of the propagation of ultrasonic pulses in the time domain using FDM (Finite Differences Method) in the multilayer structure of a biological medium [14]. Individual layers of tissue on parallel bordering planes are considered as homogeneous media with a frequency-dependent attenuation of waves. Reflection and transmitting coefficients for an ultrasonic wave at the boundaries of layers for the monochromatic propagation of the ultrasonic plane wave, are determined analytically for given angles of incidence which are smaller than limit angles. Reflection and transmission characteristics at layer boundaries are determined by numerical simulation of the propagation of broadband ultrasonic pulses calculated on the basis of peak amplitudes of ultrasonic pulses which are incident, reflected, and transferred through the layers [14]. Thus, multiple reflections within the layers are also taken into account. A similar simplified model for calculations (the angle of incidence of 0°, disregarding multiple reflections) was used in [15] for calculations of the level of reduction in the pressure amplitude of the ultrasonic wave propagated in tooth tissues for the transmission and reflection method.

As the essence of the bioacoustic link range equation is the capability to estimate the maximum decrease in acoustic power level, or acoustic pressure, of ultrasonic waves transmitted by a given sectional area of the biological medium submerged in water; therefore, complex and accurate calculations of the distribution of the sound pressure level are not necessary in this case. A good solution seems to be the use and modification of the explicit hydroacoustic link range equation (2). Biological medium immersed in water between the ultrasonic transmitting and receiving transducers can be simplified as quasi-homogeneous, or more precisely, as a multi-layered tissue structure with parallel border planes (Fig.1).

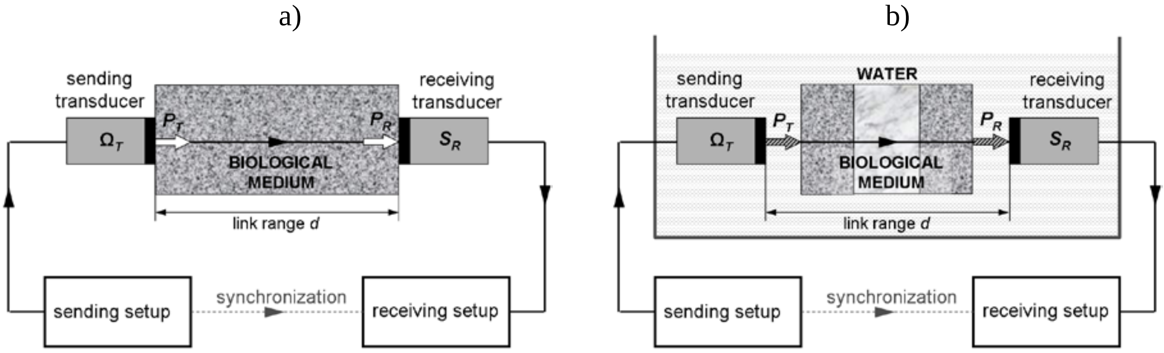

Fig. 1. Bioacoustic link model: a) quasi-homogeneous, b) multilayer.

In the case of a quasi-homogeneous bioacoustic link model (Fig.1a), the range equation can be written in the form [8]:

$$\frac{P_T}{P_R} = \frac{4\pi\, d^2 e^{2\alpha d}}{\Omega_T\, S_R}\,, \tag{4}$$

where $\alpha(f,t)$ can be assumed as the maximum value of the amplitude (pressure) attenuation coefficient of an ultrasonic wave in a studied tissue for a given frequency f and temperature t.

For a multilayer model of a bioacoustic link, shown in Fig.1b, the range equation (4) must also take into account the changes in the attenuation of ultrasound waves in individual layers, the decrease in power received as a result of transition through layers, and the impact of changes in the propagation velocity of ultrasonic waves in layers on directivity characteristics. The decrease in power received as the result of transition through the borders of individual layers can be estimated as the product of the energy coefficients of transmission defined for each border between media i and i+1 as:

$$D_{I(i,i+1)} = \frac{4\rho_i\, c_i\, \rho_{i+1}\, c_{i+1}}{\left(\rho_i\, c_i + \rho_{i+1}\, c_{i+1}\right)^2}\,. \tag{5}$$

Changes in the attenuation of the ultrasonic wave in individual layers can be taken into account by replacing the product of the mean value of the attenuation coefficient α and link length d in the formula (4) with the appropriate sum of the products of attenuation coefficients α_i for individual layers and their thickness d_i. After such modifications, the bioacoustic link range equation (4) for a multilayer model (Fig.1b) can be written as:

$$\frac{P_T}{P_R} = \frac{4\cdot\pi\cdot d^2\cdot e^{2\sum_{i=1}^{N}\alpha_i d_i}}{\Omega_T\cdot S_R\cdot\prod_{i=1}^{N-1} D_{I(i,i+1)}}\,, \tag{6}$$

where i = 1, 2, …, N – numbers of individual layers in the link.

The easiest way to take into account the effect of changes in the propagation velocity of ultrasonic waves in layers, on the directivity characteristics, is to approximate it by inserting the projection value of the speed of sound determined from the transit time of the ultrasonic wave in the link length d (from a transmitter to a receiver) into the formula for the directivity coefficient of the transmitting transducer Ω_T:

$$c = \frac{d}{\sum_{i=1}^{N} d_i / c_i}\,, \tag{7}$$

where c_i – the speed of sound in the i-th layer.

Directivity coefficient of the ultrasonic wave source can be generally determined as:

$$\Omega = \frac{4\pi}{\int_{\varphi=0}^{\pi}\int_{\theta=0}^{2\pi} K^2(\theta,\varphi)\cdot\sin\theta\, d\theta\, d\varphi}\,, \tag{8}$$

and in the case of axial symmetry (transducer with a flat circular radiating surface):

$$\Omega = \frac{2}{\int_0^{\pi} K^2(\theta) \cdot \sin\theta \, d\theta} . \tag{9}$$

The directivity of a flat circular source $K(\theta) = p(\theta)/p(0)$ can be determined based on the formula [16]:

$$K(\theta) = \left| \frac{2J_1(k \cdot a \cdot \sin\theta)}{k \cdot a \cdot \sin\theta} \right| , \tag{10}$$

where a – source radius, $k = 2\pi/\lambda$ – wave number, λ – wavelength, $J_1(k{\cdot}a{\cdot}\sin\theta)$ – Bessel function of the first kind, for the first order. Due to the axial symmetry of the circular surface of the transducer, the acoustic pressure distribution (Fig.2a) is also axially symmetric ($K(\theta) = K(\varphi)$). This function has the first zero for the argument $ka{\cdot}\sin\theta = 3.83$, which follows that the angle of beam divergence for a circular source is $2\theta_0 = 2{\cdot}\arcsin(0.61{\cdot}\lambda/a)$. In order to graphically determine the beam divergence angle, $2\theta_{3\mathrm{dB}}$ angle is often employed, which is located on the directivity characteristics between the points corresponding to a decrease of 3 dB compared to the maximum value. For a circular source, the angle $2\theta_{3\mathrm{dB}} = 2{\cdot}\arcsin(0.257{\cdot}\lambda/a)$.

The directivity of a flat rectangular source $K(\theta,\varphi) = p(\theta,\varphi)/p(0,0)$ can be determined based on the formula [16]:

$$K(\theta,\varphi) = \left| \frac{\sin\frac{ua}{2}}{\frac{ua}{2}} \cdot \frac{\sin\frac{wb}{2}}{\frac{wb}{2}} \right| , \tag{11}$$

where $u = (2\pi{\cdot}\sin\theta)/\lambda$, $w = (2\pi{\cdot}\sin\varphi)/\lambda$. Minima of this function are for the angles, for which $\sin\theta = n{\cdot}\lambda/a$ and $\sin\varphi = n{\cdot}\lambda/b$, where $n = 1, 2, 3, \ldots, \infty$, hence the beam divergence angles for a rectangular source can be determined using $2\theta_{0xz} = 2{\cdot}\arcsin(\lambda/a)$ and $2\theta_{0yz} = 2{\cdot}\arcsin(\lambda/b)$. For a rectangular source, the angle $2\theta_{3\mathrm{dB}xz} = 2{\cdot}\arcsin(0.442{\cdot}\lambda/a)$ and $2\theta_{3\mathrm{dB}yz} = 2{\cdot}\arcsin(0.442{\cdot}\lambda/b)$. If the size of the radiating surface of rectangular transducers with sides $a \approx b$, are much smaller than the length of the bioacoustic link, we can assume that the generated sound field is almost axially symmetric (Fig.2b).

On the other hand, for an axially symmetric source, for which the condition $\pi f D_T/c >> 1$ (where D_T is the source diameter, and c is the speed of sound in the medium) is met, the directivity coefficient can be determined from the simplified formula [7]:

$$\Omega_T = \frac{\pi^2 f^2 D_T{}^2}{2c^2} . \tag{12}$$

Figure 3 shows the dependence of directivity coefficient Ω_T on the source diameter D_T calculated using the formula (12) for the frequency f = 1, 2, 3, 4, 5 MHz, starting from value

D_T, for which the $\pi f D_T/c \geq 10$ condition is met. The average value of the speed of sound in soft tissue c = 1540 m/s has been used for calculations.

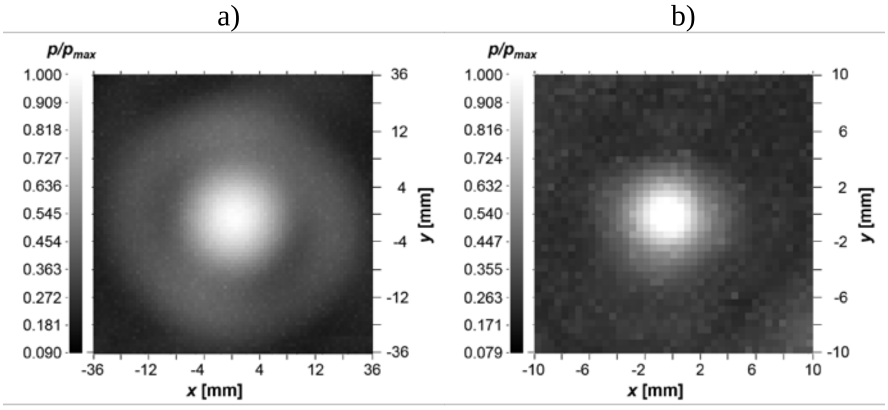

Fig. 2. Measurement results of the acoustic field distribution of an ultrasonic probe (in water, in the *XY* plane, using a needle hydrophone): a) with the circular shaped 4 MHz piezoelectric transducer of 13 mm diameter, at the distance z = 200 mm, b) with a square shaped 2 MHz piezoelectric transducer of 1.6 x 1.6 mm size, at the distance z = 25 mm.

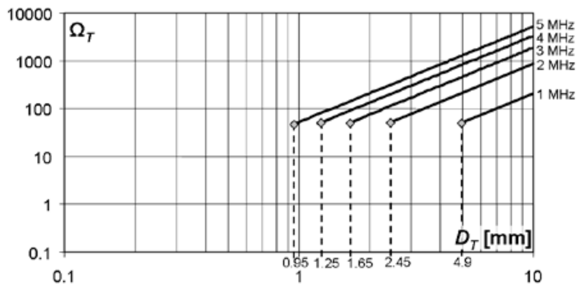

Fig. 3. Dependence of the directivity coefficient on the diameter of an axial symmetry ultrasonic wave source calculated acc. to (12) formula for some frequency values satisfying the $\pi f D_T/c \geq 10$ condition.

3. The level of acoustic power drop in the link

The radiated and received power in a bioacoustic link on the border of the near-field can be determined from measurements using formulas, respectively [8]:

$$P_T = \frac{p_T^{\,2} \cdot S_T}{2\rho c}, \tag{13}$$

$$P_R = \frac{p_R^{\,2} \cdot S_R}{2\rho c}, \tag{14}$$

where p_T – the amplitude of the acoustic pressure at the transmitting transducer axis near its surface, p_R – the amplitude of the acoustic pressure at the receiving transducer axis near its surface, ρ – the average density of the biological medium in the link, c – the average speed of sound in the biological medium in the link, S_T – the surface of the transmitting transducer, S_R – the surface of the receiving transducer.

In this way, we can estimate the decrease in the amplitude of the acoustic pressure after the passing of an ultrasonic wave through a biological medium (for the far-field), using the bioacoustic link equation:

$$L_{P_T/P_R} = 20\log\left(\frac{p_T}{p_R}\right) + 20\log\left(\frac{S_T}{S_R}\right) = L_{p_T/p_R} + 20\log\left(\frac{S_T}{S_R}\right). \tag{15}$$

In the case of tomographic measurements [15], depending on the scan sequence, the transmitting transducers are also receiving ones, then $S_T = S_R$ and a second component of the sum in equation (15) becomes zero, which gives the level of power drop equal to the level of pressure drop. Formulas (13) and (14) enable you to easily verify the calculations by measuring the amplitude of the acoustic pressure in water using a hydrophone.

4. Link range

In terms of the threshold, the link range is the distance between the transmitting and receiving transducer (the link length), for which the received power is equal to the value of the threshold signal power $P_{R_{\min}}$, determined by the required signal to noise ratio. The power ratio of the threshold signal to noise and interference in the medium can be also converted to the ratio of the squares of acoustic pressures of the threshold signal and noise. The amplitude of the acoustic pressure near the transmitting transducer is defined as the product of its effectiveness and the supply voltage amplitude at the transducer: the noise pressure amplitude can be converted to the ratio of the amplitude of the noise voltage at the pins of the receiving transducer to its sensitivity. If we regard the noise voltage as the sum of noise on the acoustic and electric side, then the range equation should additionally take into account the amplification in the receiving setup. By using some simplifications, based on formulas (13) and (14), we can derive another form of the bioacoustic link range equation (4) that allows the matching of the parameters of the transmitting and receiving setup to the limit of power drop at the link [3,8]:

$$\frac{P_T}{P_{R_{\min}}} = \left(\frac{S_n \cdot S_o \cdot U_T \cdot k_u}{U_N \cdot 10^{L_\Gamma/20}} \cdot \frac{S_T}{S_R}\right)^2, \tag{16}$$

where L_Γ – level of signal to noise ratio [dB], U_N – the amplitude of noise voltage at the receiving end, U_T – the amplitude of the supply voltage of the transmitting transducer, k_u – amplification at the receiving path, S_n – the effectiveness of the transmitting transducer in [Pa/V], S_o – the sensitivity of the receiving transducer in [V/Pa].

Another way to represent the equation range is to consider the elements of the equivalent circuit of an ultrasonic transmitting transducer in a resonance, which determine its efficiency [8]:

$$\frac{P_T}{P_{R_{\min}}} = \frac{{U_T}^2}{|Z_T|} \frac{R_p R_o}{(R_v + R_p)(R_o + R_v + R_p)} \frac{2\rho c {S_o}^2 {k_u}^2}{S_R {U_N}^2 10^{L_\Gamma/10}}, \tag{17}$$

where ρ – the average density of the biological medium, c – the average speed of sound in the biological medium, Z_T – electrical impedance of the transmitting transducer, R_o – the resistance of electrical loss at the transmitting transducer, R_v – the resistance of mechanical loss at the transmitting transducer, R_p – the radiation resistance of the transmitting transducer. The elements of the equivalent circuit for a piezoelectric transducer can be easily determined from its admittance amplitude-phase characteristics in the air, and in the biological medium or water [17]. Such an approach enables one to estimate the power drop for a selected biological medium, and the predetermined length of a bioacoustic link based on the equation (4) or (6) first, and then to design ultrasonic transducers with the transmitting and receiving setup based on formulas (16) and (17) in such a way so as to obtain the value of power drop not greater than estimated.

5. Calculations and measurements

Sample calculations of the dependence of the level of acoustic power drop on the length of a bioacoustic link in glandular breast tissue for the frequencies $f = 1 – 5$ MHz (Fig.4) were made using formulas (4) and (12). The following data were used for calculations: $t = 37$ °C, $c = 1515$ m/s, $\alpha = 0.75$ [(dB/cm)/MHz$^{1.5}$]·$f^{1.5}$, circular surfaces of transmitting and receiving transducers with the diameter of $D_T = D_R = 3.4$ mm.

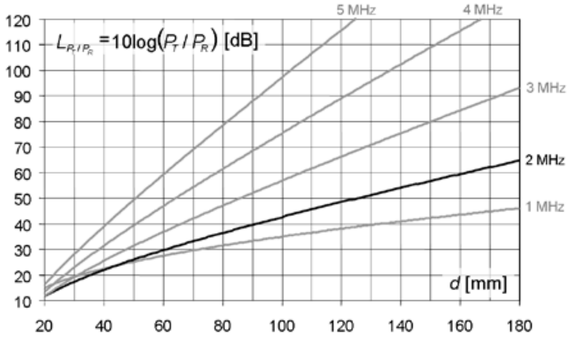

Fig. 4. Calculated dependences of acoustic power drop level on the bioacoustic link length in the breast glandular tissue for frequencies $f = 1 – 5$ MHz.

The average value of attenuation in women's breast tissue at temperature $t = 37$ °C is about 0.75±0.3 (dB/cm)/MHz$^{1.5}$ [18]. For comparison, attenuation is negligible under the same conditions in distilled water, since it is about 0.0014 (dB/cm)/MHz^2 [15]. Using the link range equation we can estimate that the level of signal weakness during the transmission cross-sectional study of a breast at a distance of about 16 cm, for the frequency of 2 MHz, will be about 60 dB (1000 times). For tomographic studies using a circular array [19] we also have to take into account the signal attenuation due to the lack of parallelism of transmitting and receiving transducer pairs; which is the greater, the greater is the angle between the transmitter-receiver axis and the diameter of the array ring. The level of such attenuation was measured for the developed circular array [19], whose interior has been filled with distilled water (Fig.5). In the circular layout of the array, the amplitude of signal transmitted from a single transmitting transducer to receiving transducers located at an angle of ±45° decreases by up to about 12 dB with respect to the amplitude from the receiving transducer located opposite to the transmitting transducer. In addition, the decrease in the range of 0 – 45° (and symmetrically in the range 0 – -45°) is approximately linear on a logarithmic scale with a slope of about 0.267 dB/°. For tomographic measurements in a divergent geometry using a circular array [15,19] the angular range of ±45° is usually sufficient (for 1024 array elements, a single measurement projection is carried out, for example, by switching on No. 0 transducer as a transmitting one and switching 256 – 768 transducers in a sequence as receiving ones).

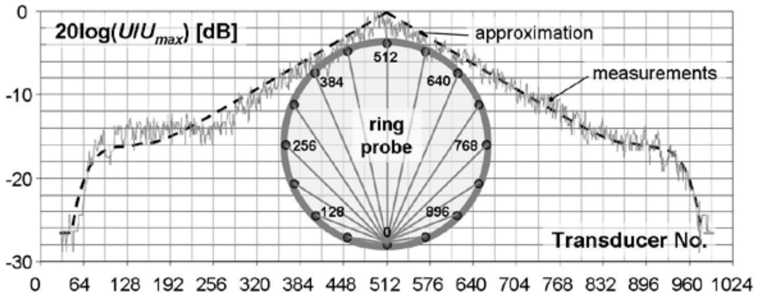

Fig. 5. The measured level of signal weakness resulting from the lack of parallelism in the pairs of transmitting and receiving transducers of the circular ultrasonic array.

Taking into account the angular signal weakness, which is compensated by a decrease in the attenuation of the ultrasonic wave due to the shortening of the link pathway for each measurement chord: the maximum total signal attenuation when scanning breast tissue using a circular array can be estimated at about 60 dB (approximately 1000 times).

Calculations of the drop in acoustic power of the ultrasonic wave after passing through a boiled and shelled hen's egg, immersed in distilled water, were also made using formula (6). The following data were used for calculations: link length d = 6.5 cm, f = 5 MHz, t = 20.2 °C, c_{water} = 1482.99 m/s, ρ_{water} = 998.2 kg/m^3, c_{white} = 1530.38 m/s, ρ_{white} = 1050 kg/m^3 c_{yolk} = 1508.68 m/s, ρ_{yolk} = 1066 kg/m^3, α_{water} = 0.054 dB/cm, $\alpha_{white} = 0.1267 \cdot f^{1.25}$ dB/cm (for f in [MHz]), $\alpha_{yolk} = 0.3822 \cdot f^{1.5}$ dB/cm (for f in [MHz]), circular area of the transmitting transducer with the diameter D_T = 5 mm, circular area of the receiving transducer (hydrophone) with the diameter D_R = 0.5 mm. Calculations were made assuming the passage through water/white/water layers (white thickness 4.1 cm) and water/white/yolk/white/water layers (total white thickness 2.1 cm, yolk thickness 3.5 cm). Acoustic parameters of water and boiled egg white and yolk were determined from the references [15,20,21], except for the speed of ultrasound, which has been determined from measurements of the transit time in such a link sequentially through water, water + white, water + white + yolk (Fig.6).

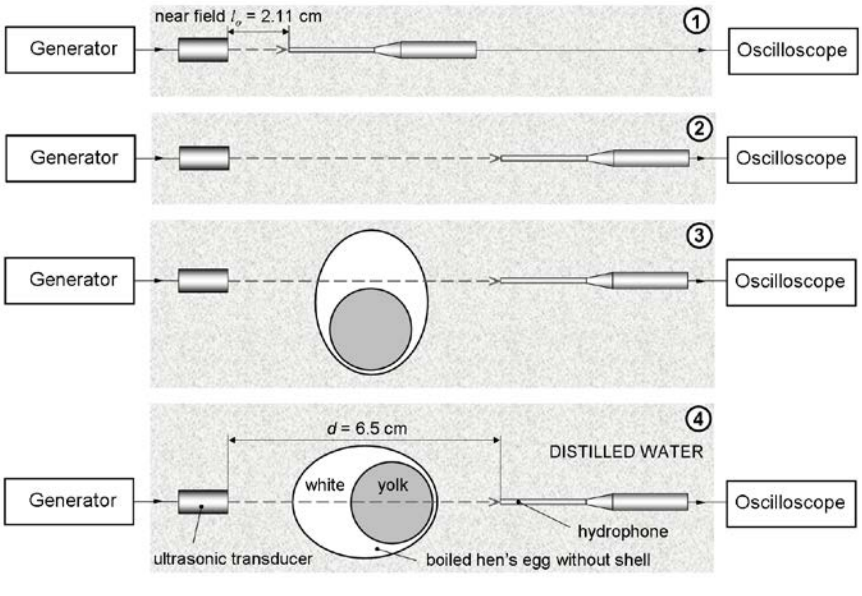

Fig. 6. A measurement system designed for the verification of calculations of the bioacoustic link with water/white/water and water/white/yolk/white/water layers (water temperature t = 20.2 °C).

The directivity coefficient of the transmitting transducer Ω_T has been determined using two different methods: accurate because – by integrating (9) the directivity characteristics of a flat circular source (10) and approximate (condition $\pi f D_T/c \approx 52$) – using the formula (12); average speeds of ultrasound after passing through the system of layers was determined using the formula (7). The calculations were made in two variants, assuming the propagation of a plane wave (according to the formula (6)), and assuming the propagation of a spherical wave by multiplying the value P_T/P_R determined from the formula (6) by a coefficient $(d/l_o)^2$, where $l_o = 2.11$ cm is the near-field of the transmitting transducer in water. The calculation results have been verified by measurements in the system with a needle hydrophone with the sensitivity $S_o = 628.5$ mV/MPa, shown in Fig.6. An ultrasonic transducer with a frequency $f = 5$ MHz and diameter $D_T = 5$ mm was used as a transmitter. Acoustic power drop levels in the bioacoustic link with a hen's egg, determined on the basis of calculations and measurements are compared in Fig.7. The levels of acoustic power drop in measurements were determined from the formula (15) based on the amplitude of the acoustic pressure p_R measured using a hydrophone at a distance of $d = 6.5$ cm from the surface of the transmitting transducer and the amplitude of the acoustic pressure $p_{T(l_o)}$ measured at the near-field distance of $l_o = 2.11$ cm from the surface of the transmitting transducer. The amplitude of the acoustic pressure p_T near the surface of the transmitting transducer was determined from the formula $p_T = p_{T(l_o)} \cdot 10^{(\alpha_{water} \cdot l_o)/20}$, where $\alpha_{water} = 0.054$ dB/cm):

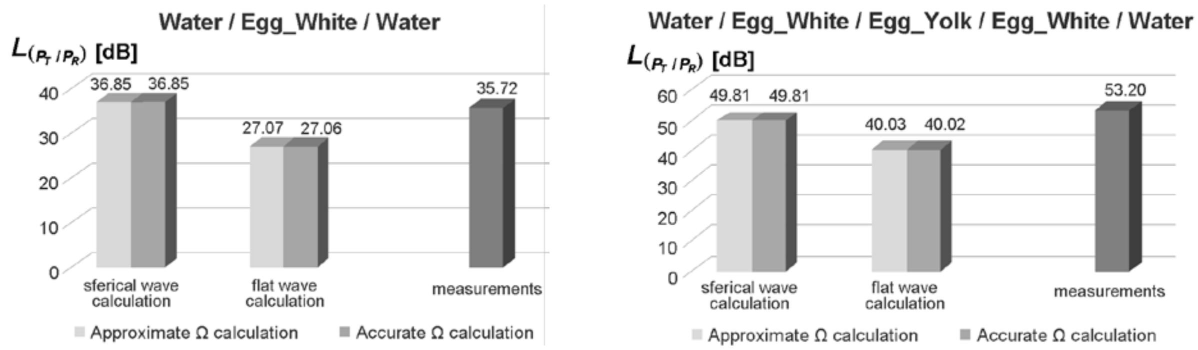
a) b)

Fig. 7. The comparison of drop levels of acoustic power determined on the basis of calculations and measurements at the bioacoustic link with layers: a) water/white/water, b) water/white/yolk/white/water.

The uncertainty of measurement of the acoustic pressure amplitude using a hydrophone, which was described as 14 % by the manufacturer, has the most significant impact on the accuracy of power drop measurements in a bioacoustic link. Assuming that the uncertainty of measurement of power drop in the link is 20 % due to the possibility of the hydrophone not aligned with respect to the transmitting transducer, the maximum uncertainty of the measurement of power drop level is 3.5 dB. The results of the measurements of the level of acoustic power drop in bioacoustic link with water/white/water layers compared with the calculation results differ by -1.13 dB in the case of spherical wave propagation, and by 8.65 dB for plane wave propagation (Fig.7). The results of the measurements of the level of acoustic power drop in bioacoustic link with water/white/yolk/white/water layers compared with the calculation results, differ by 3.39 dB in the case of spherical wave propagation, and by 13.17 dB for plane wave propagation (Fig.7). These differences may be due to the range of variation in the chemical composition and physical properties of hen's eggs – mean values of ultrasound attenuation in white and yolk were assumed for calculations. The discrepancy in the results of calculations when determining the directivity coefficient using exact and approximate methods is negligible (the total of approximately -0.005 dB in both cases), which means that the use of the approximate formula for determining the directivity characteristics of a circular source with the condition $\pi f D_T / c \geq 50$ satisfied, shows negligible differences compared to the precise method.

6. Conclusions

This paper results in equations for the estimation of the bioacoustic link range taking into account the acoustic parameters of tissues; as well as the acoustic parameters of mechanical and electrical transmitting and receiving transducers including transmitting and receiving setup. Each form of the developed bioacoustic link range equation allows the matching of the values of ultrasonic transducer parameters, and the transmitting and receiving setup to the limit of acoustic power drop at the link.

The measurement verification of the developed bioacoustic link range equation on the structure of white and yolk layers in water showed a very good agreement with calculations of the acoustic power drop level (with a maximum deviation of 3.5 dB), when assuming spherical wave propagation. This means that the calculations must be performed while taking into account the decrease in the wave intensity with the square of the distance from its source in a bioacoustic link, due to (usually) small ratios of the range to the diameter of the transducer.

By using the developed bioacoustic link range equation, the maximum signal weakness has been estimated in the scan of breast tissue using a circular array, allowing the development of elementary ultrasonic transducers of the array, together with the transmitting and receiving setups whose parameters enable you to scan breast tissue *in vivo* using the transmission mode of an ultrasound tomography device [22].

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