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# Possible temperature increases in soft tissues in the case of nonlinear and linear wave propagation

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ABSTRACT

It is well known that the nonlinear propagation increases the absorption of acoustic waves in the medium thus increasing the temperature effects. According to the recently developed new theoretical approach it is possible to determine in a simple way the effective absorption in the case of nonlinear propagation basing on the pulse spectrum analysis [Wójcik, 1996]. In this way it was possible to find the corresponding absorption values occuring in ultrasonography. In this case a classical PVDF membrane hydrophone was used to demonstrate and to measure nonlinear effects.. Analysing the obtained wave spectra it was possible to determine the increase of the effective tissue absorption and hence to find the rate of heat generation per unit volume which is crucial for temperature elevations. In this way possible temperature increases for the case of nonlinear and linear propagation can be determined.

## INTRODUCTION

The crucial problem of the obstetrical ultrasonography is the excessive generation of heat caused by nonlinear propagation of ultrasonic waves in the patient's tissue. In the case of nonlinear propagation the tissue absorption may be several times higher than in the case of linear propagation [ Bacon and Carstensen, 1990 ], [Dalecki et al., 1993]. However, up to now the analysis of the absorption during nonlinear propagation was based on the idea of the weak shock theory. In the present paper we intend to present a general and at the same time fully exact approach based on the spectral analysis of the propagating wave [Wójcik, 1996]. Also it is intended to demonstrate experimental examples of possibilities which are created by the elaborated theory.

## THEORY

Energy effects accompanying a strong sound disturbance in a medium were analyzed on the base of nonlinear acoustical equations (for instance eqn of Kuzniecov [1970], K.Z.K eqn.[Aanonsen et al.,1984]) and by means of the spectral theory of operators in relevant function spaces. One can notice that $\langle \varphi(P)\partial_t\xi(P)\rangle = 0$ if $P$ is a periodic function of $t$ or if $P(\mathbf{x},t) \to P_0(\mathbf{x})$ when $t \to \pm\infty$ for single pulses; whereas $\varphi(\cdot), \xi(\cdot)$ are any functions. It is assumed that $P = -\partial_t\Phi$; the quantities $P, \Phi, t$ are respectively dimentionless pressure, acoustical potential and time; $\langle\cdot\rangle$ denotes the time average over the period for periodic disturbances or integral over time for single pulses. Hence, in particular , in nonlinear interactions , where terms of type $\partial_t P^m$ dominate (for instance,

$m = 2$ for K.Z.K. equation) the power of disturbances is conserved. Just as in linear description, the only reason why the total power changes is linear absorption, but one that occurs under the condition of nonlinear propagation. In consequence, the equation of power balance of the disturbance have the same formal shape, although they are interpreted differently in detail, in nonlinear and linear descriptions, i.e. $\nabla \cdot \mathbf{I} + 2\langle P\mathcal{A}P\rangle = 0$, where $\mathcal{A}$ -operator of absorption (for example for classical viscous fluid $\mathcal{A} \equiv -\alpha_2\Delta$; $\alpha_2$ - dimentionless hybrid viscosity). Above relations are independent of the representation of the disturbance $P$. Particularly for Fourier representation of $P$ we have

$$\nabla \cdot \mathbf{I} + 2\sum_{n=1}^{N} a(n)\left|C_n(\mathbf{x})\right|^2/2 = 0 \qquad (1)$$

where $N = 1, 2, \ldots, \infty$

$\mathbf{I}$ is the intensity vector; $a(n)$ - small signal absorption coefficient (Fourier spectrum of $\mathcal{A}$ for periodic disturbances); $N$ - number of calculated or experimentally determined spectral component $C_n(\mathbf{x})$ of $P(\mathbf{x},t)$. The above equations provide theoretical basis for different, easier and more accurate methods than those used previously for determination for instance of. the power density of heat sources $\dot{Q}(\mathbf{x})$ generated by sound via measurement or calculation. In the previous method [Nyborg,1981] it was used the relation $\dot{Q}(\mathbf{x}) = -\nabla \cdot \mathbf{I}$, in the present one

$$\dot{Q}(\mathbf{x}) = \sum_{n=1}^{N} a(n)\left|C_n(\mathbf{x})\right|^2. \qquad (2)$$

Dividing both sides of Eqn (1) by $2 \cdot I = 2|\mathbf{I}|$ we have $a_{ef}(\mathbf{x}) = a_{r,ef}(\mathbf{x})$ where, $a_{r,ef}(\mathbf{x}) = -\nabla \cdot \mathbf{I}/2I$ - is the well known differential coefficient (function) of the effective absorption [Carstensen et al., 1982] while

$$a_{ef}(\mathbf{x}) \equiv \sum_{n=1}^{N} a(n)\left|C_n(\mathbf{x})\right|^2/2I \qquad (3)$$

is the coefficient of effective absorption introduced by us. Assuming the power dependence of the $a(n) = \alpha_l n^l$ we introduced the function of the spectral absorption $W_l(\mathbf{x})$ with $a_{ef}(x) = \alpha_l W_l(\mathbf{x})$.

So one obtains .

$$W_l(\mathbf{x}) \equiv \sum_{n=1}^{N} n^l\left|C_n(\mathbf{x})\right|^2/2I(\mathbf{x}) \qquad (4)$$

We introduced also the function of nonlinear increase of absorption, which can easily be determined experimentally or numerically, namely

$$G_a(\mathbf{x}) = a_{ef}^{NL}(\mathbf{x})/a_{ef}^{L}(\mathbf{x}) \qquad (5)$$

where $a_{ef}^{NL,L}(\mathbf{x})$ is the above defined function of effective absorption as applied for nonlinear description ($NL$) and for linear descrition ($L$) of a disturbance caused by the same boundary stimulation. By analogy

$$G_h(\mathbf{x}) = \dot{Q}^{NL}(\mathbf{x})/\dot{Q}^{L}(\mathbf{x}) \qquad (6)$$

is the function of nonlinear increase of the power density of heat sources. $\dot{Q}^{NL,L}$ is the above defined function of the power density of heat sources as applied for nonlinear description ($NL$) and for linear descrition ($L$) of a disturbance caused by the same boundary stimulation.

## NONLINEAR EFFECTS IN ULTRASONOGRAPHY

To study nonlinear effects in diagnostic ultrasound we applied a typical ultrasonic probe used in ultrasonography at the frequency of 3 $MHz$ radiating short ultrasonic pulses focused at the distance of 7 $cm$. A wave quarter matching layer assured a high acoustic output of the probe. A special switchable electrical transmitter generated electrical pulses of 320 $V_{pp}$ and 47 $V_{pp}$. In this way it was possible to study in the first case the nonlinear wave propagation while in the second one the linear propagation. At the same time the ultrasonic probe was coupled with the medium (specimen) without changing its position. So it was possible directly to compare propagation effects on the same wave path in the specimen and almost in the same time during nonlinear and linear propagation. Fig.1 shows the pressure pulse obtained in the beam focus in water when the higher voltage was applied to the probe. For measyrements we used a membrane PVDF hydrophone [Filipczyński et al.1996].One observes a high degree of wave distortions caused by the nonlinear propagation. For the lower voltage applied to the probe the wave form was not distorted and the propagation could be considered to be linear.

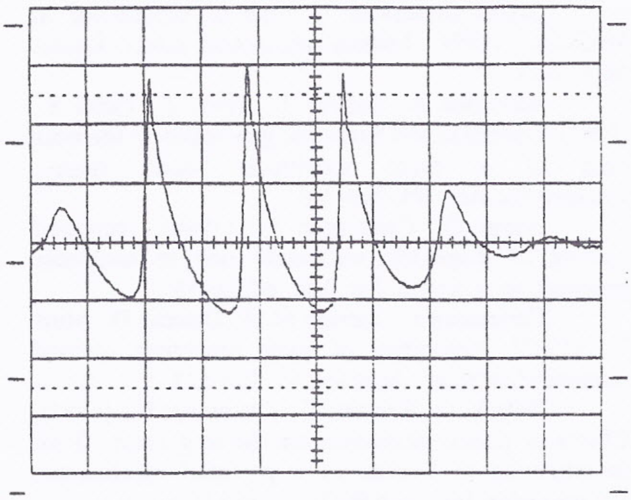

Fig.1 Pressure pulse measured in water at the distance of 7 *cm* from the radiating probe distorted due to nonlinear propagation. The maximum positive pressure value was equal to 8.3 *MPa*. Horizontal time scale - 0.2 *μs*.

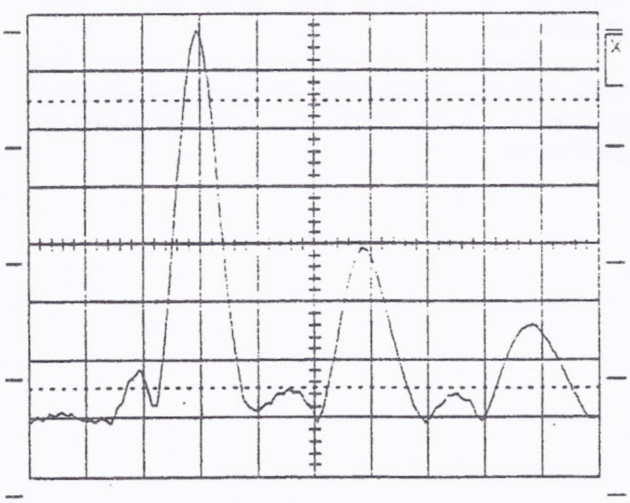

Fig.2 Amplitude spectrum of the pulse shown in Fig.1. Horizontal frequency scale - 2 *MHz*.

The intensity of the distorted pulse was determined by means of spectral analysis, since the resulting power of the distorted pulse is the sum of powers of all its harmonics. So one obtained the resulting intensity equal to

$$I = \frac{p_p^{\ 2}}{\rho c} \sum_{-\infty}^{\infty} |C_n|^2 \qquad (7)$$

where $p_p$ is the maximum positive value of the pressure pulse and $C_n$ are complex coefficients of the discrete intensity spectrum of the pressure pulse under discussion, $n$ denotes the number of the harmonic. So we determined focal intensities equal to $I_{SPPA}$ = 324 $W/cm^2$ for the nonlinear propagation and $I_{SPPA}$ = 6.0 $W/cm^2$ for the linear propagation in water.

The same measurements were carried out after placing into the ultrasonic beam animal tissue samples (from porcine kidney) 0.5, 1 and 1.5 *cm* thick. The samples were immersed in water in the distance of 7 *cm* from the radiating probe. In such a case due to nonlinear propagation higher harmonics are generated intensively in fluid which penetrate into the fetal structures increasing to a great extent their temperature.

The purpose of our study was to estimate the possibillities of temperature elevation for the same conditions when nonlinear propagation occurs.

Two basic functions characteristic for nonlinear and linear propagation were applied in our study; the function of nonlinear increse of absorption $G_a(x)$ and the function of nonlinear increase of the power density of heat sources $G_h(x)$. The function $G_a(x)$ for the ultrasonic beam determined from our experimental results in water and in tissue samples is shown in Fig.3 The maximum value of $G_h(x)$.for tissue samples was found to be equal to 2.6

## DISCUSSION AND CONCLUSIONS

The developed theory based on the spectral analysis of the propagating wave was successfully applied for the determination of the nonlinear increase of absorbsion $G_a(x)$ caused by the nonlinear propagation showing at the same time no increase for linear propagation.

When applying the ultrasonic diagnostic beam with 3*MHz* frequency the maximum nonlinear increase of absorption in water was found to be $G$ =3.8 in the focal region ($F$ = 7 *cm* ). Due to the very low small amplitude absorption in water this increase is practically not observable..On the other hand near the probe where the nonlinear effects still do not occur it was determined to be equal to $G_a$ = 1 (Fig.1).

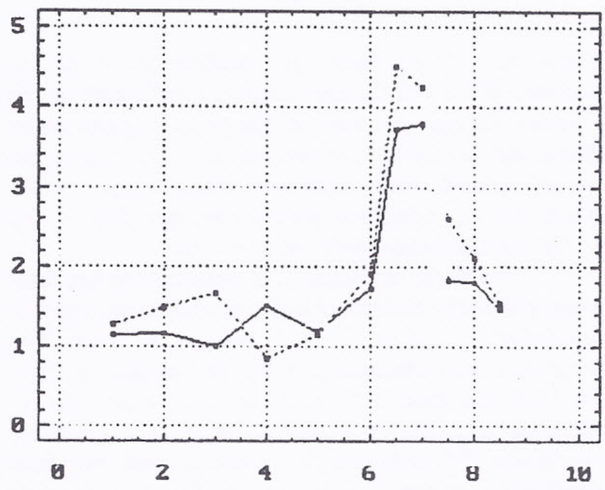


Fig 3 The function of nonlinear increase of absorption $G_a(x)$ (full curve) and of power density of heat sources $G_h(x)$ (dotted curve) determined experimentally in water (for $x$ = 1-7 *cm*) and in tissue samples (for $x$ = 7.5-8.5 *cm*). Horizontal $x$ distance scale - 1 *cm*

In the case of tissues where the small amplitude absorption is about 3 orders of magnitude higher than in water the situation is completely different for nonlinear propagation. We determined for the tissue samples 0.5 - 1.5 *cm* thick, placed in the distance of 7 *cm* from the probe, the maximum nonlinear increase of absorption for tissue samples to be $G_a$ = 1.8 (Fig. 3). And also the power density of heat sources (see eqn 6) increases 2.6 times when compared with the linear propagation. Knowing these values it is now possible to calculate the temperature elevation for the case under discussion when nonlinear propagation occurs. For linear propagation the results were published by other authors [AIUM, 1994].

In the final conclusion one can say that the new elaborated theory seems to be a very useful and an exact method in solving many complicated problems of heat generation and absorption caused by nonlinear propagation of acoustic waves. The introduced functions $G_a(x)$ and $G_h$ $(x)$ are good characteristics of nonlinear interactions.

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