Ultrasound tissue characterization using transmission tomography combined with measurement of the integrated backscatter

ULTRASOUND TISSUE CHARACTERIZATION USING TRANSMISSION TOMOGRAPHY COMBINED WITH MEASUREMENT OF THE INTEGRATED BACKSCATTER

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ABSTRACT

The objective of this paper is to describe an extension to an ultrasound transmission tomograph that is able to process the backscattered signal. With the tomograph it was already possible to make images of three local acoustical parameters of an object: the sound velocity, the attenuation coefficient and the attenuation slope. In addition to these parameters the energy contained in the backscattered signal also represents a useful index for quantitative tissue characterization. The developed extension is able to determine the integrated backscatter. By doing this a requirement for the reconstruction algorithm is satisfied: the measured quantity can be written as a line integral of a two-dimensional distribution of a physical quantity in the scan plane. The combination of the four images and the knowledge of the local value of the parameters make the apparatus a powerful instrument for tissue characterization.

Key words: Ultrasonic imaging, Ultrasound transmission tomography, Tissue characterization, Integrated backscatter, Sound velocity, Attenuation.

INTRODUCTION

During the last two decades, diagnostic ultrasound has been used as a non-ionizing means for quantitative tissue characterization. It has been recognized that pathological tissue exhibit acoustic properties significantly different from normal tissue. Hence, the quantitative measurement of the acoustic properties of tissue has become an important area of research [1],[2],[3],[4].

The most common approach to determine the acoustic properties of tissue is to analyse the radio-frequency echo signals containing information about the acoustic properties. A less common, but an approach full of promises is to use the information contained in the transmitted pulse.

Ultrasound transmission tomography was first described by Greenleaf at al. in 1974 [5], followed by Carson et al. [6] and later it has been studied by several investigators. Although various applications have been indicated [7],[8], up to now this technique has not been accepted in clinical practice. The ultimate goal of our research project is to develop an ultrasound transmission tomograph based on a personal computer, that may be used in clinical practice. We decided to provide this tomograph with the possibility to process the backscattered signal.

ULTRASOUND TRANSMISSION TOMOGRAPHY

The objective of this paper is to describe the extension to the transmission tomograph that is able to process the backscattered signal. Before this extension was realized the transmission tomograph was able to image three local acoustic parameters: the sound velocity, the attenuation coefficient and the attenuation slope [9].

The sound velocity is determined using a time-of-flight measurement. This measurement is done by a reverberation technique [10].

The attenuation coefficient is determined by means of an amplitude measurement. The amplitude of the received pulse is measured using a electronic peak detection circuit.

The attenuation in tissue is frequency dependent. The higher frequencies are more attenuated than the lower ones. Hence, the center frequency will shift downwards when a pulse travels through tissue. The center frequency downshift is determined using a zero-crossing technique [11].

Reconstruction Algorithm

The information that is extracted from the received pulse is mapped into images using the direct Fourier inversion algorithm [12]. In order to obtain a cross-sectional image of the object this cross-section has to be scanned. A set of linear projections is obtained at a variable number of angles between 0 and 180 degrees.

The direct Fourier inversion algorithm estimates the two-dimensional distribution of a certain variable x using the measured linear projection. A condition that must be satisfied is that the measured value F(t) has a one-to-one relationship with a line integral of the two-dimensional distribution of a physical quantity x(s,t) in the scan plane.

$$F(t) = C \int_L x(s,t)\, ds \qquad (1)$$

For the time-of-flight measurement this condition is satisfied since each measured value is the total of all time-of-flight values at small parts ds on the path between the transducers. The time-of-flight value on ds at position s, when v(s,t) is the local sound velocity, is ds/v(s,t). So, the total time-of-flight between the two transducers at a position t is

$$T(t) = \int_L \frac{1}{v(s,t)}\, ds \qquad (2)$$

The attenuation coefficient of an ultrasound pulse can be written as

$$\ln\left(\frac{A_r}{A_0}\right) = -\frac{1}{2}\int_L \alpha(s)\, ds \qquad (3)$$

where A_0 and A_r are the amplitudes of the transmitted and received pulses respectively. In order to determine the value of the line integral in Eq. (3) from the measured amplitude of the received signal A_r, the amplitude of the transmitted signal A_0 must be known. The total center frequency downshift can be written in first order approximation as

$$\Delta\overline{\omega} = \sigma^2 \int_L \frac{d\alpha}{d\omega}_{\omega=\overline{\omega}_t}\, ds \qquad (4)$$

σ is a measure for the width of the pulse. It can be seen that the center frequency downshift of a pulse travelling along the ray L is proportional to the line integral of the derivative of $\alpha(\omega)$ at the center frequency of the transmitted pulse.

BACKSCATTERING

The set-up developed so far did not use the information contained in the backscattered signal. On the basis of several studies suggesting that the energy contained in the backscattered signal represents a potentially useful index for quantitative tissue characterization [13], [14], [15], we decided to develop an extension for the ultrasound tomograph that is able to process the backscattered signal.

Backscattering appears as a result of acoustic inhomogeneities in tissue. The first quantitative study of the laws of scattering by small particles was made in 1871 by Rayleigh and such scattering is frequently called Rayleigh scattering.

As we might expect the scattered intensity is found to be proportional to the incident intensity and to the square of the volume of the scattering element. The most interesting result, however, is the dependence of the scattering on wave length.

$$I_s = k\,\frac{1}{\lambda^4} \qquad (5)$$

In power spectrum measurements the backscatter is transformed and a spectrum is obtained. Backscatter from a sample volume of tissue can be described in the frequency domain as

$$V(\omega) = P(\omega)\, B(\omega)\, T^2(\omega) \qquad (6)$$

$V(\omega)$ is the receiver output signal.

$P(\omega)$ is the transfer-function associated with the characteristics of the transducer and the characteristics of electronics. $P(\omega)$ is measured by substituting the sample volume with a plane, nearly perfect reflector.

$B(\omega)$ is the backscatter transfer-function. This function describes the efficiency with which ultrasound is backscattered at each frequency. The efficiency is determined by the scattering properties of the sample volume.

$T^2(\omega)$ describes the propagation effects such as attenuation.

Integrated Backscatter

Integrated backscatter is defined as the frequency average of the backscatter transfer-function [16].

$$IBS = \frac{\int_{-\infty}^{\infty} |P(\omega)\, B(\omega)|^2\, dt}{\int_{-\infty}^{\infty} |P(\omega)|^2\, dt} \qquad (7)$$

Although the integrated backscatter can be computed straightforward using Eq. (7), the processing becomes clumsy because two Fourier transforms must be computed for each measurement.

If we define

$$V^*(\omega) = P(\omega)\, B(\omega) \qquad (8)$$

then, applying Parceval's theorem [17] on both the numerator and the denominator, Eq.(7) becomes

$$IBS = \frac{\int_{-\infty}^{\infty} |v^*(t)|^2\, dt}{\int_{-\infty}^{\infty} |p(t)|^2\, dt} \qquad (9)$$

Thus the integrated backscatter can be obtained by first correcting the received pulse for the attenuation, represented in Eq. (6) by the factor $T^2(\omega)$. Then the total energy in the signal backscattered from a volume of tissue is measured and the result is normalized to the energy in the signal when the sample is substituted by a nearly perfect reflector.
The integrated backscatter is a relative measure of the ultrasonic energy backscattered by a volume of tissue. The backscatter transfer-function is directly related to the scattering properties of the tissue. If we use the integral in the denominator for the direct Fourier inversion method, we also image a coefficient that depends on many scatter parameters (size, shape, density, distribution, etc.). This coefficient provides a useful index for tissue characterization.

IMPLEMENTATION

The realization of the echo-receiver is shown in the block-diagram of Fig.1. It has been designed taking into account the foregoing requirement about the line integral. A next requirement was that after the implementation of the echo-receiver it should be possible to perform all four measurements at the same time during the scanning process.
The front amplifier provides an initial amplification of the received signal (backscattered echo train). A protection circuit is added at the input of the amplifier to protect it from being damaged by the high voltage pulse that triggers the transducer to send a pulse. The amplifier is specifically designed using a video amplifier to amplify small signals, as echo signals are.
In order to account for attenuation of the ultrasonic field as it propagates through tissue, a global time gain compensation (TGC) has been applied. By applying an amplification that increases exponentially with time, it is possible to compensate approximately for the attenuation.
A full-wave rectifier and a low-pass filter together form an envelope detector. The full-wave rectifier is one also used in commercial available echo scanners.
After the envelope detector a correction circuit allows correction for the noise that is always present in addition to the backscattered signal. The correction should be made before the object is placed between the transducers. Another condition for the reconstruction algorithm requiring zero measured value outside the object is also satisfied by this correction.
The integrator produces the integral over time of the envelope of the rectified signal r(t).

$$I = \int_{-\infty}^{\infty} |r(t)|\, dt \qquad (10)$$

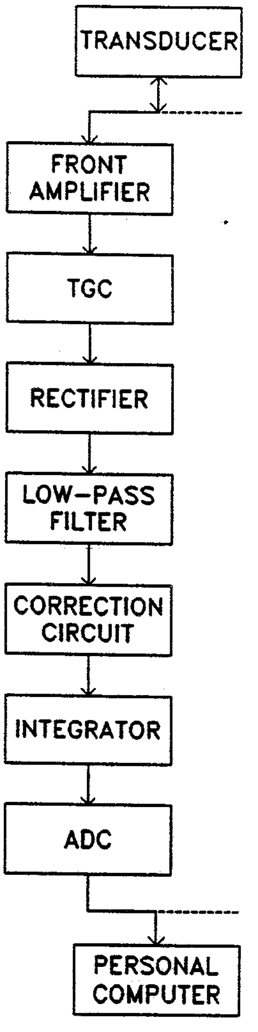

Fig. 1. Block diagram of the echo receiver

The output signal of the integrator is interfaced to the computer by means of an A/D converter.

DISCUSSION

Comparing Eq. (10) with the equation for the integrated backscatter (Eq. (9)), two main differences can be seen. The in Eq. (9) defined integrated backscatter is related to the energy in the backscattered signal if the sample is replaced by a nearly perfect reflector. In the tomograph it is impossible to obtain the signal from a perfect reflector, because intercepting the beam with such a reflector would spoil the transmission measurement.
The denominator in Eq. (9) is the total energy contained in the signal $v^*(t)$, that is v(t) corrected for attenuation. The measured integral (Eq. (10)) is not exactly the energy contained in the signal but it can be

expected to be proportional to it.

MEASUREMENTS

At this moment only preliminary results can be presented. Measurements have been performed with the described set-up on tissue mimicking phantoms made of agar-agar with some insertions of another material with known geometry and acoustical properties. In this case iron-oxide powder (Fe_2O_3) was added because of the scattering properties of the iron-oxide particles. Images were reconstructed from measurements from phantoms made of agar-gel solely in which internal structures of agar-gel with iron-oxide powder were brought in.
In Fig. 2 an image of a cylindrical phantom (diameter 50 mm.) with a cylindrical insertion of 15 mm. diameter (agar-gel with 5.3% Fe_2O_3) is shown.

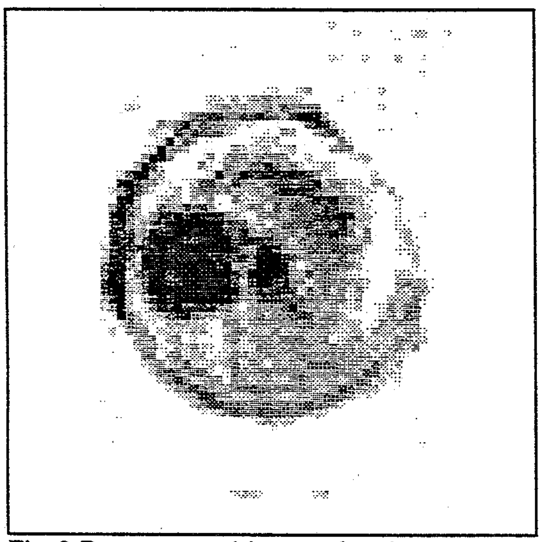

Fig. 2 Reconstructed image of a phantom

The little dark circle in the middle of the phantom is an artefact introduced by the sample of which the sound beam is perpendicular to the tangent to the phantom.

CONCLUSIONS

The difference in scattering between the bulk and the inserted structure in the phantom shown in Fig.2 is clear recognizable. We might conclude that by using Eq. (10) in the direct Fourier inversion method, we image a coefficient that is useful in tissue characterization. The value of the imaged parameter is known on every position in the image. A combination of this parameter and the three parameters, determined from the transmitted pulse, makes it possible to do quantitative tissue characterization.

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