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An In Vivo Technique for Estimation of Size and Relative Sound Velocity of Breast Tumor using Distorted Image in Ultrasonic Tomogram

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A technique is proposed for estimation of size and sound velocity of a massive tissue relative to its surroundings that is larger with ultrasonic beam width. This technique is based on a distorted image of a plane reflector behind a massive tissue in an ultrasonic tomogram, which is caused by ultrasonic refraction. An example of a breast tumor with an obscure boundary is shown to demonstrate the usefulness of this technique.

§1. Introduction

In recent years, ultrasonic equipment has been widely used in clinics for medical diagnosis. Most of this equipment displays information on a human body by emitting an ultrasonic pulse into the body and receiving reflected pulses at the interfaces of organs. This ultrasonic equipment enables us to acquire information for medical diagnosis non-destructively and without causing bleeding to the patient. The intensity level of ultrasonic radiation does not harm the human body, and the equipment can be used even in an unborn baby safely.

Sometimes it is difficult to extract useful information in a medical diagnosis due to a lack of understanding of an ultrasonic image or the piece of equipment that projected it. For example, the distorted image of an ultrasonic tomogram can provide us with much information on the inhomogeneity within an organ; this distortion is related to the sound velocity distribution in the organ.

Okujima et al. pointed out that ultrasonic beam refraction distorts an image behind a massive tissue. Therefore, analysis of the phenomenon of distortion is made based on the difference in sound velocity. But they proposed no estimation technique for the sound velocity distribution in the organs.

Here, we have investigated quantitatively the relation between the phenomenon of these distorted images and the sound velocity of a cylinder relative to that of its surroundings. An vivo technique utilizing the characteristics of distorted images is proposed to estimate the size and sound velocity of a massive tissue. An example of a breast tumor with an obscure boundary is shown to demonstrate the usefulness of this technique.

§2. Analysis of Echogram

2.1 Refraction of Acoustic Ray at Cylindrical Boundary

When the dimensions of a cylinder are much larger than the wavelength of the ultrasonic pulse, the propagation of ultrasound through the cylinder can be analyzed by the acoustic ray theory. Refraction of an acoustic ray at the boundary of the medium in which ultrasound travels at a different velocity can be expressed by Snell's law.

In the linear scan of an ultrasonic beam, acoustic rays are refracted at the cylindrical boundary as shown in Fig. 1, where Snell's law is applied. In Fig. 1(a) sound velocity \( c_2 \) in the cylinder is greater than the sound velocity \( c_1 \) in the surroundings (that is \( c_2 > c_1 \)). The angle of refraction is greater than the angle of incident; thus, the acoustic rays diverge. In this case, when angle of incident is greater than \( \sin (c_1/c_2) \), the critical angle, the incident ultrasonic beam is not transmitted through the cylinder but is reflected totally. Inversely, when \( c_2 \) is smaller than \( c_1 \), the acoustic rays converge as shown in Fig. 1(b).

2.2 The Echogram of a Plane Reflector behind a Cylinder

Shown in Fig. 2 is a case where in a medium of sound velocity \( c_1 \), there is a cylinder of radius \( r \) with sound velocity \( c_2 \) behind this cylinder a plane reflector was placed. Because of the ultrasonic refraction, the image of the plane reflector behind the cylinder is distorted and is represented by a curve with lateral tails (Fig. 2(b)).

The curve can be expressed by the following equation:

\[
y' = h + \frac{y - h}{\cos \theta} + 2r(n \cos \theta_2 - \cos \theta_1) + x \tan \theta \tag{1}
\]

As shown in Fig. 2(a), linear scanning axis to get the circumference of the cylinder is the distance from its center axis by \( h \), taking the origin of the coordinate on the \( x \)-axis and facing the \( y \)-axis downward. The angle of incident \( \theta_1 \) is settled depending on the position of \( x \), the angle of refraction \( \theta_2 \) is determined by Snell's law, and the
angle of refraction $\theta$ after passing through the cylinder equals $2(\theta_t - \theta)$, and refraction index $n(=c_l/c_i)$.

When there is an ultrasonic target on point $P(X, Y)$, the distance of $x$ will be settled by the acoustic ray passing through this point; the distance of $y'$ can be determined by means of expression (1). According to the above transformation, in the ultrasonic echogram, point $P$ is displayed by point $Q(x, y')$, as shown in Fig. 2(b).

§3. Estimation Technique

Usually, it is difficult to measure directly the lateral size of a cylinder from its image when the cylinder surface is smooth, as shown in Fig. 3. But it is easy to estimate the size when there is a plane reflector behind it. The lateral size and longitudinal size of the cylinder can be obtained from 1) the distance between the parts of broken plane image $MN$, or the distance of lateral tails of a plane image, and 2) the sum of $D$ and $d$, respectively.

Therefore, the sound velocity in the cylinder relative to that of the surroundings $c_s$ shown in Fig. 4. can be calculated using the following equation:

$$c_s = \left(1 + \frac{d}{D}\right)c_i$$  \hspace{1cm} (2)

where $D$ is the width of the image of the cylinder in the direction of the beam and $d$ is the height of the convex part of the plane image (negative when it is concave).

Figure 4 shows the measurement technique of relative sound velocity in a cylinder from the distorted image of a plane reflector. Figure 4(a) is a cylinder with higher velocity, while Fig. 4(b) is a cylinder with lower velocity.

Fig. 2. Plane reflector and its displayed image under ultrasonic beam refraction.

Fig. 3. Images of a cylinder and a plane reflector.

Fig. 4. Measurement technique of sound velocity in a cylinder relative to the surroundings from a distorted image. $D$: width of the cylinder image in the direction of the beam, $d$: height of the convex or concave part of a plane image, $MN$: width of the broken part of a plane image.

§4. Ultrasonic Echogram Model

A tomogram of a massive tissue such as a tumor and its posterior echogram is distorted because of the effect of ultrasonic refraction. Usually it is a spherical shape that causes the ultrasonic beam to refract, but here, a cylinder is used which is capable of producing a stable echogram easily, and which also produces refraction for research on ultrasonic echogram distortion. The results would be similar to those expected on spherical objects.

Cylinder phantoms of known velocity are required for experimental evaluation of distorted image. For this purpose, where the phantom's velocity is equal to or faster than that of water, we have developed agar phantoms containing saccharose, which is the main controller of ultrasonic velocity. For the phantom of lower velocity, a silicon rubber is used.

Behind the cylinder phantom is placed a rough surface plane reflector, which always projects its image even if the incident ultrasonic pulse is slanted, as shown in Fig. 5.

§5. Experiment and Simulation

As shown in Fig. 5, a cylinder (radius $r=25$ mm) with dimensions much larger than the width of the ultrasonic beam is immersed in water. A rough surface plane reflector is placed 15 mm behind this cylinder with sound velocity $c_2$ which is used in two cases, one is with sound velocity of 1550 m/s which is faster than 1470 m/s, the velocity of sound in the surroundings (water), and the other is with 1000 m/s which is slower than the surroundings. The ultrasonic tomograms of these cases are shown in Fig. 6(a) and (b).

The sound velocity of the cylinder can be obtained from the distortion of the plane image. In Fig. 6(a) the
height of the convex part of the plane image $d$ is 3 mm, the width in the direction longitudinal to the cylinder image $D$ is 48 mm. Thus, take the sound velocity $c_1$ in the surroundings to be 1470 m/s, from eq. (2) the sound velocity in the cylinder $c_2$ is 1561 m/s. Similarly, in Fig. 6(c) the height of $d$ is 22 mm, the width of $D$ is 70 mm; thus, the velocity in the cylinder $c_2$ is 1008 m/s. In these cases, the error of the sound velocity is estimated at around 1%.

Apart from the character of the echogram in Fig. 6(a) and (c), the results of simulating calculation based on the acoustic theory of Fig. 6(b) and (d) are comparable.

As shown above, from the unevenness of the distorted image of the plane reflector behind a cylinder, the sound velocity in the cylinder relative to that of the surroundings can be estimated. Sound velocity is higher than in the surroundings when the image is convex (distorted toward) and lower when it is concave (distorted away). Furthermore, the sound velocity of the cylinder can be evaluated from the width of the cylinder image $D$ and the height of the unevenness, part $d$, of the plane image.

Figure 7 is an example of an ultrasonic tomogram of a breast tumor with an obscure boundary. From this tomogram, it is difficult to measure directly the lateral size of the tumor, but when there is a plane reflector such as the breast wall behind the tumor, its size can be estimated from the distance of the lateral tails in the image of the breast wall. Its sound velocity could also be estimated from this image distorted toward or away by this tumor. We estimated that the sound velocity of this particular tumor was faster than that of the surroundings, because the image of the breast wall distorted toward. This result shows the usefulness of this technique.

§6. Conclusion

We have investigated a technique for estimating the size and sound velocity of a massive tissue relative to its the surroundings that was larger with ultrasonic beam width. Its size was estimated from the distance between the parts of broken plane image or the distance of the lateral tails in the image of the plane reflector, and its sound velocity was estimated based on the image of the plane distorted toward or away by this massive tissue. Furthermore, its value could be determined by the shift of this plane image and the width of the massive tissue in the direction of the ultrasonic beam in the ultrasonic tomogram. The example of a breast tumor with an obscure boundary demonstrated the usefulness of this technique.

References