Ultrasound Phantom Using Thin Wires for the Depiction of Calcification

— Comparison of Cross-Sections of Wire Targets and Mass Targets —

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We report on a technique to construct an ultrasound calcification phantom using wires. Employment of the proper angle of the measurement plane to a wire target can adjust its effective size to that of a mass target. To acquire this angle of the measurement plane we compared the scattering cross-sections of 0.2, 0.1, 0.05 and 0.03 mm diameter copper wires, and copper cylinders that are 0.2 and 0.1 mm in size. The experiments were conducted using a commercial ultrasonographic device with a 7.5 MHz linear array probe. The scattering cross-section of a wire is severely reduced as the angle of the measurement plane to that wire decreases. At a depth of 2 cm the scattering cross-sections of the 0.2 and 0.1 mm copper cylinders are equivalent to the scattering cross-section of a 0.1 mm diameter copper wire, when the measurement plane angles to the wire are 87.6 and 87.0 degrees for the 0.2 and 0.1 mm copper cylinders, respectively. This result indicated that the employment of the proper angle of the measurement plane can adjust the effective size of a wire target to the size of a mass target, and consequently fulfills the requirements for use as a calcification phantom.

Keywords : ultrasonography, calcification, scattering cross-section, effective size, ultrasound phantom

1. Introduction

Ultrasonography (US) provides a great deal of information about soft tissue that is important for the diagnoses of various diseases. However, US has a limited ability to detect calcifications compared with X-ray imaging such as X-ray computed tomography and mammography. The existence of calcifications not only causes pain and various diseases but also indicates the presence of lethal diseases. Renal calcification causes acute pain, kidney infection and hydronephrosis. Gallstones are intensely painful. The existence of diffuse calcifications in the breast indicates breast cancer. Because US is a convenient, safe and effective clinical imaging tool involving no exposure to ionizing radiation, improvement in its calcification detection ability is desirable.

Many researchers have proposed medical ultrasound imaging techniques to improve the spatial resolution of US. Tissue harmonic imaging (THI) is one of the techniques that have been used to improve the spatial resolution of US. THI suppresses speckle artifacts and improves contrast resolution; however, the calcification detection ability of THI is considerably lower than that of X-ray imaging. Other researchers have employed a cell-averaging constant false alarm rate (CA CFAR) to depict calcification. The CA CFAR extracts targets from non-stationary noise and clutter while maintaining a constant probability of a false alarm. Therefore, CA CFAR detectors can depict calcifications with high-intensity echoes but can rarely detect small calcifications. This is due to the fact that they have inconspicuous echo intensities as compared with the surrounding tissue.

To enable the depiction of calcifications without high-intensity echoes, we have proposed a calcification depiction method for US using decorrelation of echoes (CDDE) caused by calcifications. Since CDDE inspects the waveform change caused by a calcification, it can depict a wire of diameter 0.05 mm that is only faintly depicted in a B-mode image due to its slight echo intensity. CDDE also results in clear depiction of a calcification that is faintly depicted in a B-mode image; however, the employment of a small mass target to mimic a calcification results in difficulty in confirming that the mass target is located in the measurement plane. Therefore, we have previously investigated the performance of CDDE for ultrasonography in the depiction of calcification using wire targets. Because a calcification is a kind of mass target, the evaluation of the performance of CDDE requires that the effective size of the wire targets and mass targets be similar. Since the angle of the measurement plane to a wire is supposed to strongly influence the scattering cross-section of a wire target, the employment of the proper angle of the measurement plane is expected to adjust the scattering cross-section of the wire target to that of a mass target. Stanton reported analytic solutions relating to sound scattering by cylinders of infinite and finite lengths; however, in this work the end effects of the cylinders were neglected. In the present study, we have experimentally investigated the scattering cross-sections of wire targets and mass targets using a commercial US device. We propose the proper angle of the measurement plane to a wire target to adjust the effective size of the wire target to that of a mass target to enable the construction of an ultrasound calcification phantom using wire targets.

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2. Materials and Methods

2.1 Comparison of the Scattering Cross-Section of Wire Targets and Mass Targets

Fig. 1 shows the schema for calcification depiction using CDDE. Since a calcification has a large acoustic impedance mismatch to soft tissue, creeping waves around the calcification surface, diffraction waves and multiple reflection waves in the calcification occur when a calcification exists in a scan line. When these waves occur at a calcification they cause the waveform of the ultrasound echo to change, and as a consequence the echo waveform of a scan line with a calcification is quite different from that without a calcification. This difference between the echo waveform of a scan line with or without a calcification causes decorrelation of the echoes at and behind a calcification. Thus, the method depicts calcifications using cross-correlation between adjacent scan lines in an ultrasound B-mode image. CDDE has the potential to depict small calcifications that are undetectable in ultrasound B-mode images, and to approximate the performance of a US imager to that of an X-ray imager in terms of calcification depiction. In order to evaluate the performance of the method a calcification phantom with small targets that have inconspicuous echo intensities in comparison with their surroundings is needed. When a small mass target is employed its low echo intensity makes it difficult to confirm that it exists in a measurement plane. The employment of thin wire targets guarantees that the targets exist in all measurement planes. Therefore, we employed thin copper wires to investigate the performance of CDDE\(^{(13)(14)}\). Calcification is a kind of mass target, and thus in evaluating the performance of CDDE in the depiction of calcification using US, the effective size of a wire target and a mass target should be similar. We thus investigated the scattering cross-sections of wire targets and mass targets experimentally.

The diameters of the copper wires and the sizes of the copper cylinders were all smaller than the beam width of the US device. This means that the echo intensity in a scan line at the target depth corresponds to the scattering cross-section of the target when the target is located close to the center of the scan line. As a consequence, we used the maximum echo intensity of a single scan line around the position of a wire target as the indicator of the scattering cross-section of the target, \(P\).

\[ P \propto \max_{x,z} I(x, z), \]  

where \(x\) and \(z\) are respectively the lateral and vertical components of a pixel in a B-mode image, \(S\) is the region around a copper wire, and \(I(x, z)\) is the echo intensity of a pixel in a B-mode image. Because the echo from a wire target has a specular echo component, the angle of the measurement plane to the wire is expected to strongly influence the echo intensity at the position of the wire. To acquire the proper angle of the measurement plane to adjust the scattering cross-section of a wire target to that of a mass target, we surveyed the variation in the scattering cross-sections of wire targets in response to variations in the angle of the measurement plane to the wires. Fig. 2 shows the scattering geometry of a copper wire.

The calculation of the scattering cross-section of a copper cylinder requires that the cylinder exists in the measurement plane. Therefore, we scanned the linear array probe to select the maximum echo intensity around the position of the cylinder.

2.2 Experimental Setup

This study was mainly designed to depict calcifications that accompany breast cancers. We thus set the measurement depth at 1 to 3 cm. Since mammography can depict small calcifications of 0.2 and 0.1 mm in size\(^{(17)(18)}\), the depiction of small calcifications of the same sizes using CDDE is desirable. Therefore, we employed mass targets of 0.2 and 0.1 mm in size. The scattering cross-section of a wire
target is supposed to be larger than that of a mass target. For this reason we experimentally compared the scattering cross-sections of wire targets that were 0.2, 0.1, 0.05 and 0.03 mm in diameter and mass targets that were 0.2 and 0.1 mm in size. First, we prepared 4% agar gel block phantoms with wire targets embedded at depths of 1, 2 and 3 cm in three separate containers. Each phantom had four copper wires with diameters of 0.2, 0.1, 0.05 and 0.03 mm. Fig. 3 shows the experimental apparatus used in this study and Fig. 4 shows a B-mode image of a phantom with four wires. Next, we used copper cylinders that were 0.2 mm in size in each cross-section was normalized to the maximum scattering cross-section of a 0.2 mm diameter copper wire at the same depth. A small decrease in the angle of the measurement plane to a wire largely suppressed the scattering cross-section of the wire. This result means that the prime component of the echo from a wire target is the specular echo and indicates that this component is suppressed when the angle of the measurement plane is not perpendicular to the wire.

The 0.1 and 0.05 mm diameter wires had very similar scattering cross-sections at a depth of 3 cm. The scattering cross-section of a rigid and fixed cylinder of infinite length at the forward scattering direction in a far field was reported by Stanton

\[
P_{\text{wire}} \propto \sum_{m=0}^{\infty} (-1)^m \varepsilon_m \frac{J_m'(ka)}{J_m(ka)}^2, \quad \text{..................................(2)}
\]

\[
\varepsilon_m = \begin{cases} 1 & (m = 0) \\ 2 & (m \geq 1) \end{cases}, \quad \text{.......................................................(3)}
\]

where \( m \) is an integer, \( k \) is the wave number, \( a \) is the radius of the cylinder, \( J_m'(x) \) is the derivative of the Bessel function of the first kind of order \( m \), and \( H_m'(x) \) is the derivative of the Hankel function of order \( m \). This solution is derived from the well-known formulation for the scattering of sound by an infinitely long cylinder in a cylindrical coordinate system with the condition of a plane wave incidence. This solution introduces the following assumptions. First, that there was no absorption, dispersion, or
nonlinearities in the cylinder or surrounding medium. Second, that this solution does not support shear waves. In addition, that the end effect of a cylinder was not important. Applying this formula at the frequency of 7.5 MHz, the scattering cross-sections of the 0.1, 0.05 and 0.03 mm diameter wire targets are $-5.27$, $-5.53$, and $-11.0$ dB, respectively, where they are normalized to that of a 0.2 mm diameter wire target. When the angle of the measurement plane is 88 degrees or less, the phase rotation of the echo from a wire occurs on an element surface. In this condition the signal received by an element is approximately equivalent to the sum of the two signals received at both ends of the element. Stanton(16) employed a point transmitter and a point receiver, and thus the experimental condition that uses a small angle of the measurement plane approaches the condition supposed by this author. As shown in Fig. 7 (c), when the angle of the measurement plane to the wires was 88 degrees, the scattering cross-sections of the 0.1, 0.05 and 0.03 mm diameter copper wires were $-3.65$, $-4.89$ and $-8.91$ dB, respectively, where they were normalized to that of a 0.2 mm diameter copper wire at a depth of 3 cm. When the angle was 87 degrees, the scattering cross-sections of the 0.1, 0.05 and 0.03 mm diameter wires at a depth of 3 cm were $-4.25$, $-3.95$, and $-7.54$ dB, respectively. Thus, in the theoretical study and in the experimental study, the scattering cross-sections of the wires 0.1 and 0.05 mm in diameter were very close. These results support the validity of the experimental study.

The scattering cross-sections of the 0.2 mm copper cylinders had a larger variance than that of the 0.1 mm cylinders. The scattering cross-section of a finite cylinder without the end effect was calculated as follows(16):

$$P_{\text{ln}} \propto L^2 \left( \frac{\sin(kL \cos \theta)}{kL \cos \theta} \right) \sum_{m=0}^{\infty} (-1)^m e_m \frac{J_m'(Ka)}{H_m^{(1)}(Ka)} \right)^2$$

where $L$ is the length of a cylinder, $\theta$ is the angle between the incident direction of an ultrasound pulse and the cylinder axis, as shown in Fig. 8, and $K = k \sin \theta$. This solution was derived from the integration of the volume flow per unit length along the length of the cylinder(20) with the same assumptions at the solution of Eq. (2). Because this formula neglects the end effect of a cylinder, it cannot be applied when $\theta$ is smaller than 45 degrees due to the effect of the echo from the cylinder edges. Fig. 9 shows the variation in the scattering cross-sections of the 0.2 and 0.1 mm cylinders calculated by the formula, where each value of the scattering cross-section has been normalized to the maximum scattering cross-section of the 0.2 mm cylinder. This formulation...
shows that at the frequency of 7.5 MHz the scattering cross-section of the 0.2 mm cylinder is severely suppressed when $\theta$ is close to 60 degrees. In contrast, the scattering cross-section of the 0.1 mm cylinder reduces gradually in response to a decrease in $\theta$. These results indicate that the scattering cross-section of a 0.1 mm cylinder is less dependent on the direction of the cylinder axis, in agreement with the lower variance of a 0.1 mm copper cylinder investigated experimentally.

When the angle of the measurement plane to the wires was 90 degrees the scattering cross-sections of the wires was much larger than that of the cylinders. In contrast, a decrease in the angle of the measurement plane suppressed the scattering cross-sections of the wires to a less extent than that of the cylinders. Table 1 shows the angle of the measurement plane that was required to adjust the mean scattering cross-sections of wire targets to those of mass targets, where we utilized a logarithmic interpolation. The standard deviations of the scattering cross-sections of the 0.1 and 0.2 mm cylinders are listed in parentheses, where each was a linear value normalized to the standard deviation of the scattering cross-section of the wire after angle adjustment.

<table>
<thead>
<tr>
<th>Cylinder of 0.2 mm in size</th>
<th>Cylinder of 0.1 mm in size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth of 1 cm</strong></td>
<td></td>
</tr>
<tr>
<td>0.2 mm</td>
<td>86.2° (0.90)</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>86.2° (0.90)</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>87.5° (1.7)</td>
</tr>
<tr>
<td>0.03 mm</td>
<td>89.3° (3.3)</td>
</tr>
<tr>
<td><strong>Depth of 2 cm</strong></td>
<td></td>
</tr>
<tr>
<td>0.2 mm</td>
<td>86.3° (0.56)</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>87.6° (0.86)</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>87.6° (0.61)</td>
</tr>
<tr>
<td>0.03 mm</td>
<td>87.9° (0.81)</td>
</tr>
<tr>
<td><strong>Depth of 3 cm</strong></td>
<td></td>
</tr>
<tr>
<td>0.2 mm</td>
<td>86.7° (0.70)</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>87.3° (0.89)</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>87.3° (0.58)</td>
</tr>
<tr>
<td>0.03 mm</td>
<td>87.9° (0.72)</td>
</tr>
</tbody>
</table>

Subsequent to angle adjustment the variation in the scattering cross-section of a wire was different to that of a cylinder, as shown in parentheses in Table 1. This difference caused the disparity between the detectability of the cylinders and the wires. We thus investigated the cumulative values of the scattering cross-sections of the cylinders and a 0.1 mm diameter wire, where we assumed that the scattering cross-section of each type of target followed a normal distribution. Fig. 10 shows the detectability of 0.1 and 0.2 mm cylinders as compared with the detectability of a 0.1 mm diameter wire after angle adjustment. Each point in Fig. 10 indicates a cumulative value of the scattering cross-section of a wire and a cylinder at a given scattering cross-section value. This result showed that the detectability of a 0.2 mm cylinder approximates to that of a 0.1 mm diameter wire after angle adjustment; however, the estimation of the detectability of a 0.1 mm cylinder from the detectability of a wire requires compensation (Fig. 10). The employment of the angle adjustment with compensation, taking into consideration the variation in the scattering cross-section, will provide an experimental setup for the evaluation of an ultrasound calcification depiction method using wire targets.

4. Conclusion

For the construction of an ultrasound calcification phantom using wires, we investigated the angle of the measurement plane to a wire as a method for adjusting the effective size of a wire target to that of a mass target. To acquire the proper angle of the measurement plane we compared the scattering cross-sections of 0.2, 0.1, 0.05 and 0.03 mm diameter copper wires and 0.2 and 0.1 mm copper cylinders, where the target depths are 1, 2 and 3 cm. The standard deviations of scattering cross-sections of the 0.1 and 0.2 mm cylinders are listed in parentheses, where each was a linear value normalized to the standard deviation of the scattering cross-section of the wire after angle adjustment.

**Fig. 10.** Detectability of 0.1 and 0.2 mm cylinders as compared with the detectability of a 0.1 mm diameter wire after angle adjustment.
were conducted using a commercial ultrasonographic device with a 7.5 MHz linear array probe. It was found that the scattering cross-section of a wire severely reduced as the angle of the measurement plane to the wire decreased. When the angles of the measurement planes to the wire were 87.6 and 87.0 degrees, the scattering cross-section of a 0.1 mm diameter copper wire was equivalent to those of 0.2 and 0.1 mm copper cylinders at a depth of 2 cm, respectively. Since the variation in the scattering cross-section of a 0.2 mm cylinder was similar to that of a 0.1 mm diameter wire after adjustment of the angle of the measurement plane, the detectability of a 0.2 mm cylinder approximated to that of a 0.1 mm diameter wire after angle adjustment; however, there was considerably less variation in the scattering cross-section of a 0.1 mm cylinder than in the scattering cross-section of a 0.1 mm diameter wire after angle adjustment, resulting in a necessity of compensation in order to estimate the detectability of a 0.1 mm cylinder from the detectability of a wire. This finding indicated that the employment of the proper angle of the measurement plane and appropriate compensation of detectability using the variation in the scattering cross-sections adjusted the effective size of a wire target to the size of a mass target, and consequently fulfilled the requirements for use as a calcification phantom. Future work will involve investigation of the performance of CDDE in calcification detection using the calcification phantom proposed in this study.

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References


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