Three-Dimensional Dynamic Imaging by a Spherical Pulsed Wave of Ultrasound

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1 Introduction

Ultrasonic diagnostic devices are widely used to observe the structure of internal organs[1] and measure the blood flow velocity in vessels[2] noninvasively. However, in conventional echography which requires scanning of a narrow and directional beam, it is impossible to image a two-dimensional(2-D) plane area instantaneously. Since the scanning speed is restricted by ultrasound velocity which is not fast in vivo, there is a time gap in a echogram. For example. the reconstruction of a dynamic image with a frame rate of 30 results in the time gap of 30msec. Moreover, the time gap would be much larger to visualize three-dimensional(3-D) domain area. When a fast moving object like an aortic valve or a blood vessel is measured, the time gap can not be neglected. The concept of our research is to overcome this problem and to visualize such as stenosal area in a blood vessel.

Some investigators have suggested a 3-D imaging method to improve this problem[3], [4]. The time gap is reduced a lot by using pyramidal scanning with a phased-array transducer in the method. This method may be effective in visualizing static objects. However, it is not fit to observe moving objects such as a human heart or a blood vessel because it also needs scanning. On the other hand, other researchers have reported methods to visualize a human heart or the inside of a blood vessel[5],[6]. They synthesize a 3-D ultrasound image using off-line reconstructions of serial cross-sectional clinical scans. It is impossible to reconstruct 3-D images in real time yet. For reconstruction of an instantaneous 2-D echogram, we have developed an imaging method using a fan-beam and a linear array probe without scanning[7]. Moreover, we have suggested a 3-D imaging method, in which a transmitter illuminates a measurement domain using a spherical pulsed wave and some receivers detect echo signals as acoustic holography and also we have reported static imaging results using a sliced ham and a rabbit heart[8].

In this paper, we describe the spatial resolutions of the 3-D imaging method, fundamental applications to dynamic imaging and so on. It begins with a description of the experimental system that enables us to capture the echo signal and to reconstruct the

3-D object image, A description of experimental results obtained using a butter block and a copper plate in water, discussions and conclusions follow. The conclusions contain a summary of key results.

2 Experimental System

Figure 1 shows the experimental system consisting of the 2-D transducer array(aperture size:3mm, resonance frequency:10MHz), the pulse generator (Hewlett Packard 8116A, voltage: 5V, pulse duration: 50nsec), two digital storage oscilloscopes (LeCroy 9314L, sampling frequency: 100MHz, 8bits, memory capacity for data stock: 1Mbyte/channel, the number of channels: 4), a personal computer(Apple Macintosh Quadra/700) and an image processing workstation(Silicon Graphics Onyx Reality Engine^2).

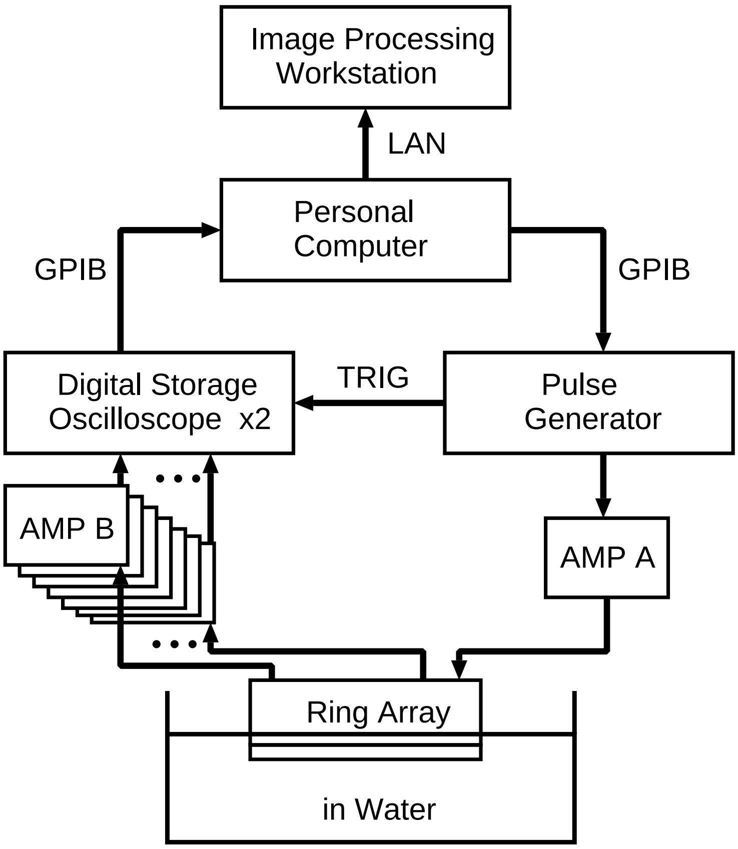


Figure 1: A block diagram of the experimental system consisting of a 2-D transducer array, a pulse generator, digital storage oscilloscopes, a personal computer and an image processing workstation.

Confirmed in our previous paper[8], the 3-D static image reconstruction is performed as shown in Fig.2. A 3-D dynamic imaging is performed with repeating the previous reported 3-D imaging[8]. In experiments, the number of the pulse repetition is fixed to 20 and the frequency is set to 10 or 100Hz. The vast amount of image data is once buffered in the digital storage oscilloscopes. After measurement the data are transferred to the image processing workstation through LAN(Local Area Network) and the dynamic image is reconstructed and displayed on the workstation. Thus a bistatic dynamic 3-D image is displayed using a depthcueing method. The 3-D image was observed from a fixed view point so far. On the other hand, the image can be seen from a variable view point.

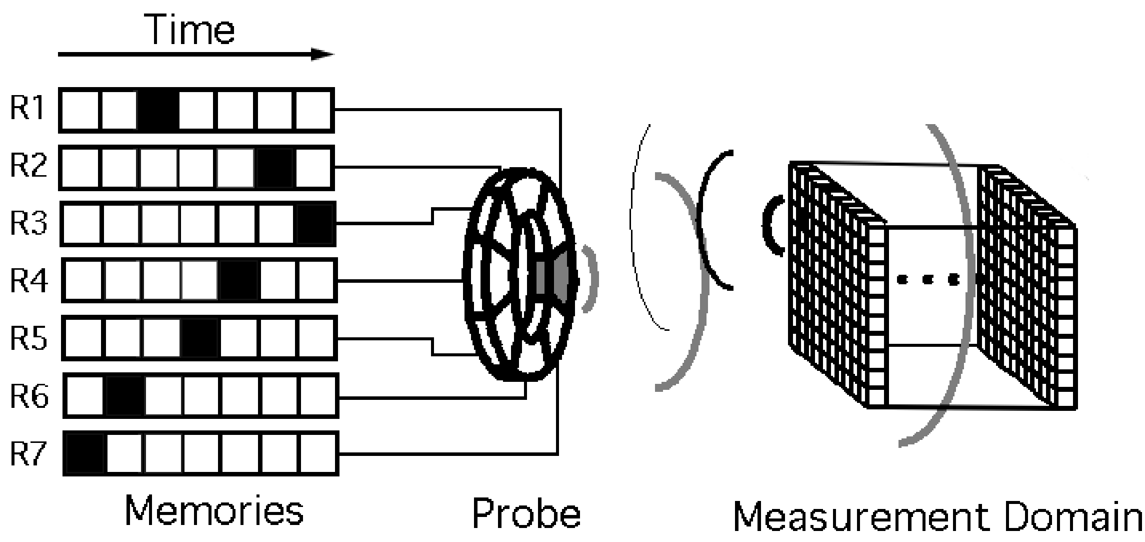


Figure 2: The method for reconstructing a frontal 3-D view, in which a non-directional spherical pulsed wave is transmitted to a measurement domain, the echo travels from the object to receivers of the phased fan-shaped ring array, and the output of each receiver is stored in the specific pattern on the memory.

3 Experimental Results

3.1 Spatial resolutions

Spatial resolutions are specified with an axial resolution and a lateral resolution. The former means a resolution in the depth direction of the domain area and the latter a resolution in azimuth directions of C-mode(constant depth mode) images. In order to examine the spatial resolutions, the experiments were performed using a copper plate with a 1.8mm diameter hole. In the experiments, the copper plate was positioned at the various distances from the probe, and the 3-D images including the hole were reconstructed. Reconstructed positions of the plate and reconstructed diameters of the hole in the image were examined. The example of a result, twenty C-mode images, is shown in Fig.3.

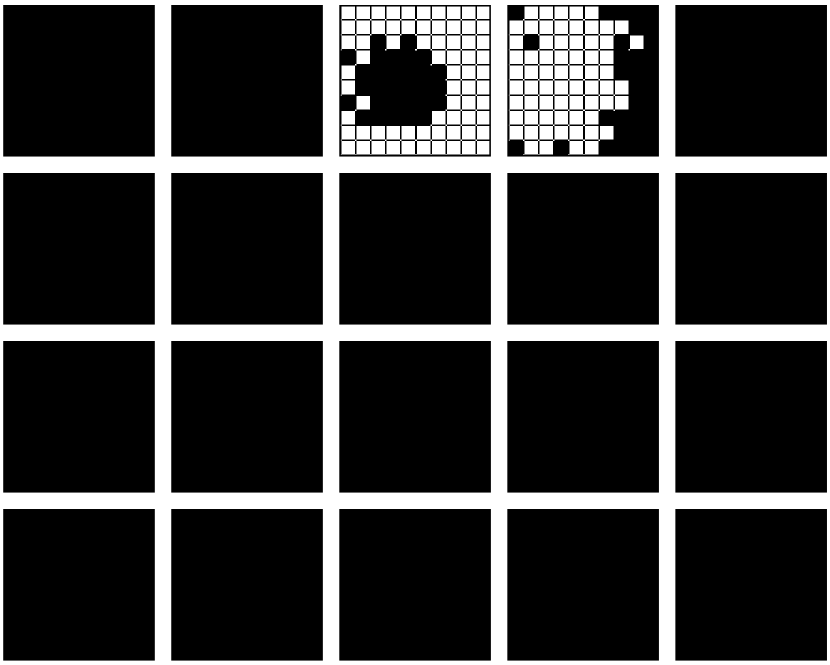


Figure 3: The example of a result, twenty C-mode images, is shown. The distance between the probe surface and an image becomes larger(10mm – 19.5mm) from left to right image and and from top to bottom row.

The distance between the probe surface and an image becomes larger(10.0 – 19,5mm) from left to right image and from top to bottom row. Figure 3 shows objects exist at 11.0 – 11.5mm from the probe. Because a hole was seen at 11.0mm, the reconstructed distance and diameter were 11.0mm and 2.4mm, respectively, for this case. The image at 11.5mm was thought to be a ghost image. The results were summarized in Fig.4.

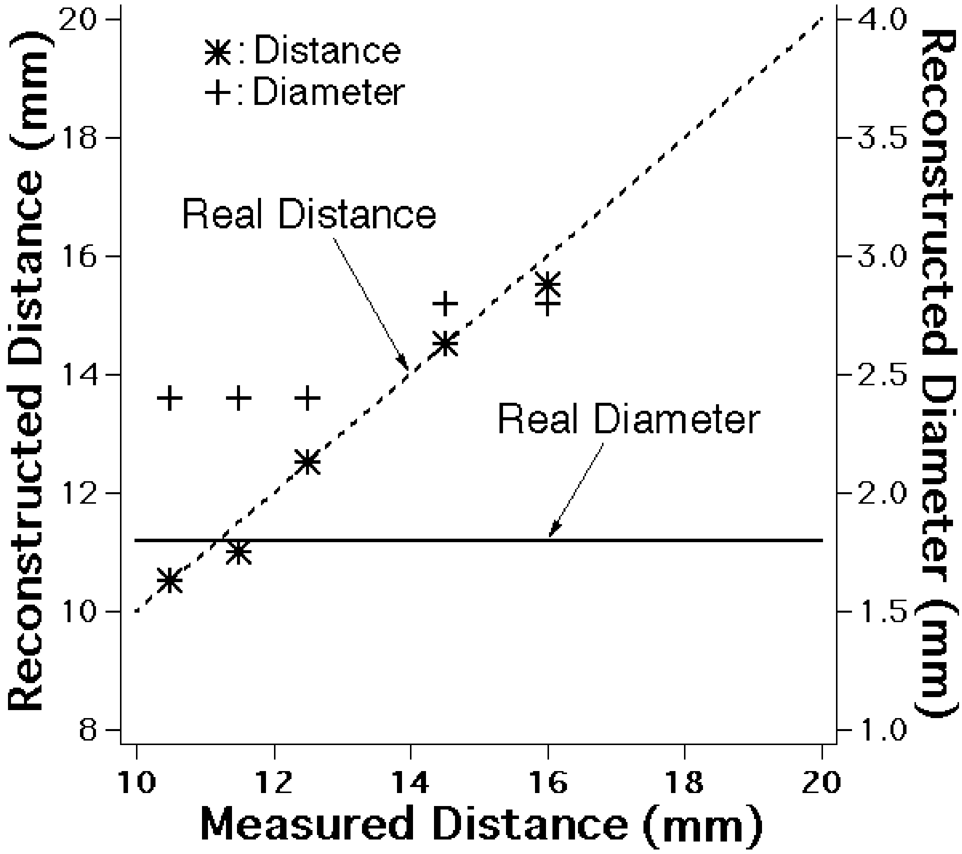


Figure 4: The dependency of the reconstructed distance between a probe surface and a copper plate and the reconstructed diameter of a hole in the copper plate upon the measured distance, where dotted and solid line indicate the real distance and diameter and asterisks and crosses indicate the reconstructed distance and diameter, respectively.

In the figure, each reconstructed position is in good agreement with the real position, while about 1.0mm difference exists between the real diameter and the reconstructed. Moreover, the difference becomes larger as the measured distance becomes bigger. Therefore, the lateral resolution is depend on the distance from the probe.

In the conventional method, the axial resolution depends on the wave length of ultrasonic beam, and the lateral resolution the width of the beam. On the other hand, in this method which does not need beam scanning, the axial and lateral resolutions mainly depend on the wave length λ of ultrasound. When the ultrasound frequency is 10MHz and the propagation velocity in water is 1,500m/sec, λ is 0.15mm. Thus the axial resolution is thought to be about half the wave length and the lateral resolution several times of the wave length.

3.2 Measurements of a butter block

The experiments were carried out using a butter block, which was located at 12.5mm – 16.5mm from the surface of the ring array probe and jammed in a plastic tube. In the experiments, the pulse repetition frequency was set to 100Hz. The reconstructed 3-D frontal image of the butter at 0.0sec after the beginning of measurement is shown in Fig.5.

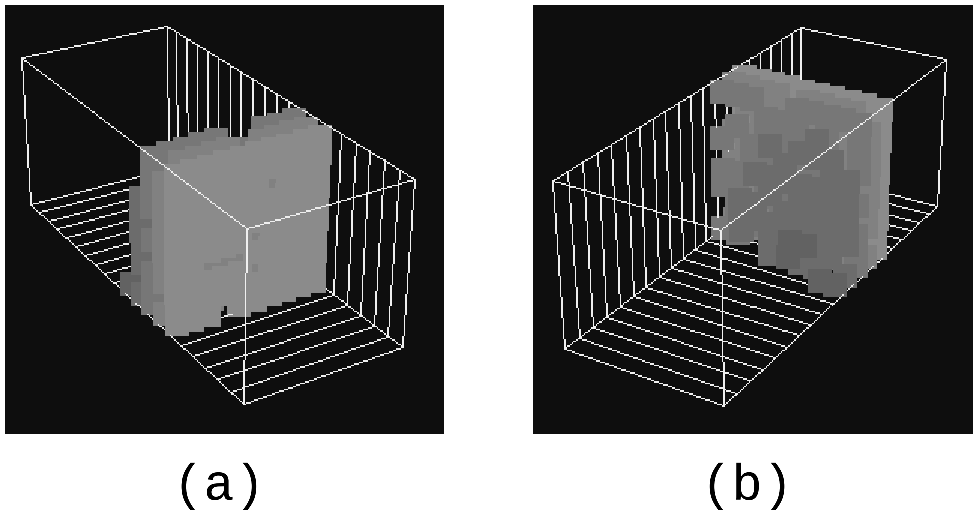
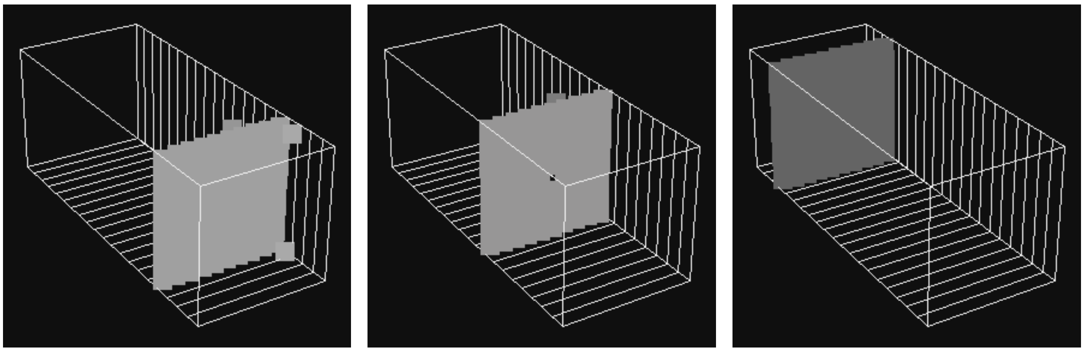


Figure 5: The 3-D images of a butter block, which is reconstructed by zooming-up and over-drawing C-mode images in descending order of their distance from the probe. The reconstructed 3-D image can be observed from a variable view point; (a) frontal view (b) backward view.

In the figure, the butter block was visualized from 13.0mm – 15.0mm ahead of the probe. The reconstructed 3-D image can be observed from a variable view point.

3.3 Measurements of a moving copper plate

We applied this method to a moving object. A plain copper plate was placed in front of the probe, and the probe was manually pulled apart from the plate when we began measurement. In this experiment, the pulse repetition frequency is set to 10Hz. Figure 6 shows the results of this experiment.



(a) (b) (c)

Figure 6: The 3-D images of a copper plate on 0.0sec(a), on 0.8sec(b) and on 1.6sec(c) after stating measurement, which are reconstructed by zooming-up and over-drawing C-mode images from left-upper to right-lower corner in descending order of their distance from the probe.

Though small parts vanished by thresholding[8], this figure, including 3-D images on 0.0, 0.8 and 1.6sec after the beginning of measurement, demonstrates that we succeeded in reconstructing a moving object instantaneously.

4 Discussions

4.1 Image sensing rate

It takes $2DN/C$ to reconstruct an ultrasound B-mode(brightness-mode) image with a conventional ultrasonic diagnostic device, where D is the maximal depth of field, N is the number of scanning lines, and C is the speed of wave propagation. Moreover, it takes longer to reconstruct a 3-D image. On the other hand, this method requires only $2D/C$ because the measurement domain is illuminated instantaneously by an ultrasonic spherical pulse, and it is thus possible to acquire the echo data in very short time using this method. In fact, data acquisition time of a 3-D image is about 27μsec, where D = 20mm and C = 1,500mm/sec in vivo. Thus image sensing rate could be raised up to about 3700image/sec in this method. Therefore, it is obvious that the method is effective in reconstructing a moving object like a blood vessel and in obtaining a real-time 3-D echogram.

4.2 Spatial Resolutions

As seen in Fig.4, this method has good spatial resolution in an axial direction, while the resolution in a lateral direction is more or less than 1.0mm and is not sufficient for observation of small area such as the insides of a blood vessel. In order to get high spatial resolution in the lateral direction, there are some techniques as follows;

1. a M-sequence (maximum period sequence) modulation method is used instead of the pulse modulation method[9],
2. some 3-D images acquired with an element for transmitting sequentially changed are averaged using an advantage of the high image sensing rate of this method.

The former technique needs complex system configurations and needs much longer time to complete all processes. On the other hand, the latter technique would not be so difficult. Moreover, the technique would not only make the spatial resolutions better but also reduce speckle noises and artifacts in the ultrasonic images. Thus, the latter is more effective in practical use. Any disadvantages resulting from averaging of several images hardly effect on high-speed data acquisition of this method since data acquisition time is much smaller than the period of video-rate(30msec/frame). For the dynamic imaging at video-rate (30frame/sec), over 1,000 echographs can be averaged because the upper-limitation of the image sensing rate is 3,700image/sec. Thus higher-resolutional image reconstruction could be performed with the the averaging technique.

5 Conclusions

A new 3-D ultrasonic imaging system has been advanced. Using our method, a 3-D dynamic image is obtained instantaneously. The experimental results obtained using a butter block and a copper plate show that the system is fit for the correct measurement of the object depth position and form, and the results also indicate the possibility to observe stenosal portions in blood vessels or movements of valves of human heart in real-time. Since the lateral resolutions can be improved by using techniques described above, our method would be very effective in clinic.

In the future, real-time processing systems using DSP chips will be helpful in observing the inside of structures such as cardiovascular vessels.

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