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Sector-scanning 3D ultrasound imaging in frequency domain with 1D array transducer

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ABSTRACT

Sector-scanning is a conventional scanning mode in ultrasound imaging, which can increase the area to observe. In three-dimensional (3D) ultrasound, freehand imaging system is usually used. This method uses a moving elevation focused one-dimensional (1D) transducer to construct a series of B-mode slice images, and then these B-mode slice images are combined to form a 3D volume image. When sector-scanning is used to acquire the B-mode slices, the elevation resolution is poor because of the elevation resolution of the probe and the interpolations between the slices. In this paper, based on the linear scanning method in our previous work, a sector-scanning 3D imaging method is proposed. In this imaging method, a linear array transducer without elevation focusing is also used, and the 1D transducer transmits limited diffraction beams and receives echo signals repeatedly when rotated around an axis parallel to the transducer. After finishing the scanning, all the received signals are combined to construct the 3D image in frequency domain with Fourier transform. Simulation results show that the new method can construct the 3D image effectively. Compared with the imaging method based on B-mode slices, the new method can improve the elevation resolution significantly. The elevation resolution can be promoted to less than 2 mm with the imaging depth 100 mm by one transmission at each position. Besides, because only one transmission is needed at each position, the frame rate can be increased to some extent.

1. Introduction

Ultrasound imaging technique has been widely used in medical diagnosis and clinical applications. In the recent three decades, 3D ultrasound imaging was developed, and has been shown as a more promising tool [1–3]. Compared with the B-mode imaging, 3D ultrasound imaging can provide the spatial anatomic structures, which is more helpful for the surgeons. The 3D images can be constructed from a series of related B-mode images or obtained directly with a 3D probe [4]. Because of the complexity of the 2D array transducer, the 3D ultrasound imaging method based on the slices of B-mode images is a common way to acquire 3D images [5,6]. In this method, a series of B-mode images are constructed when the 1D array transducer is located at different positions. Then, these B-mode images are combined to form a 3D volume according to the position information. The 1D array transducer can be moved using a mechanical device or manually. There are two main problems should be solved. Firstly, when the transducer is moved manually, motion tracking technology is needed [7]. Secondly, when the slices of B-mode images are not acquired with line and uniform scanning, interpolations are needed to perform, and a reconstruction algorithm should be used for combining the B-mode slices to 3D volumes [8].

The 3D ultrasound imaging with B-mode slices has advantage of lower cost. However, a drawback of the 3D ultrasound imaging with B-mode slices is that the resolutions are not isotropic. In the plane of the B-mode images, the resolutions are the same with the original B-mode images. While, in the direction of scanning route, the resolution is affected by the elevation resolution of the probe used for imaging [4]. The reason is that: in order to acquire the B-mode slices, the probe is designed with a fixed elevation focus. The width of sound field at the focus is most narrow, and it increases with the propagation distance away from the focus. Generally the elevation resolution is determined by the width of sound field in the elevation direction. So the elevation resolution is best at the focus, and decreases with the propagation distance away from the focus [9].

Except the elevation resolution of the probe, the reconstruction algorithm will also affect the resolution. In a more practical situation, the slices of B-mode images are not acquired with line and uniform scanning, and interpolations are needed to perform [10], that affect the resolution in the direction of scanning route. For example, as a special no linear scanning, sector-scanning can be

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used to acquire the B-mode slices. However, these slices represent the pixels in cylindrical coordinate system, and should be converted to the final images in rectangular coordinate that is used for display. This conversion is mainly based on the interpolations, and will affect the resolution. Fig. 1 is the plane perpendicular to the rotation axis. In this plane, the conversion can be performed from polar coordinate to rectangular coordinate. This is the same to B-mode imaging with sector-scanning. Therefore, a digital scan converter (DSC) can be used to perform the interpolations [11,12]. As shown in Fig. 1, the pixel values in polar coordinate that marked with filled circle can be acquired by sector-scanning imaging directly, while the pixel values in rectangular coordinate that marked with empty circle need to be interpolated from the filled circles around. The sampling density for the filled circle is sufficient in the near imaging depth, while it will decrease seriously in the large imaging depth. Therefore, the interpolation precision decreases with the imaging depth increasing, which reduces the resolution in the elevation direction. For the 3D ultrasound imaging with B-mode slices, the current researches are mainly focus on the algorithm of interpolation. However, this can not solve the elevation resolution affected by the elevation resolution of the probe as described ahead.

Synthetic aperture (SA) focusing technique has shown a significant increase in resolution [13,14]. In order to increase the elevation resolution, the time of flight is calculated to perform the synthetic aperture focus [15]. However, SA focusing technique in time domain needs to calculate the precise time of flight from each pixel of the image to every receive element, which needs high computational cost. Some methods are proposed to reduce the computational complexity to some extent [16], and frequency domain imaging algorithms is an alternative to reduce the computational cost [17].

Except the resolution, the frame rate is also important for the imaging system. For freehand 3D imaging system, the lateral and depth resolution is usually determined by the B-mode slice images. In order to acquire the high quality B-mode images, multi-transmitting is usually needed, which reduces the frame rate.

In order to improve the elevation resolution and frame rate with low computational cost, in our previous work, a 3D ultrasound imaging method in frequency domain with a moved one-dimensional (1D) array transducer is presented [18]. In this method, a linear array transducer without elevation focusing is used, and the 1D transducer transmits limited diffraction beams and receives echo signals repeatedly when moving along the elevation direction (Fig. 2(a)). After finishing the scanning, all the received signals are combined to construct the 3D image in frequency domain with Fourier transform. This method can improve the elevation resolution significantly, and the frame rate can be increased to some extent. However, this method is only suitable to linear-scanning, and the imaging area is a cuboids ahead the probe.

In this paper, this imaging method is extended to sector-scanning by solving the nonlinear problem in theory, which can increase the area to observe. Similar with the linear scanning imaging method, a linear array transducer without elevation focusing is also used in the extended method. Different from the linear scanning used in the previous work, in the new method, the 1D transducer is rotated around an axis parallel to the transducer that realizes the sector-scanning imaging (Fig. 2(b)). The 1D transducer transmits limited diffraction beams and receives echo signals repeatedly when rotated to each position. After finishing the scanning, all the received signals are combined to construct the 3D image in frequency domain with Fourier transform. Compared with the conventional sector-scanning method using the rotated elevation focused 1D array transducer, this new method can improve the elevation resolution. Because of the use of Fourier transform, the computational cost can be reduced. While sufficient imaging quality can be achieved by only one transmission at each position, the frame rate can be increased to some extent.

2. Theory

In order to extend the linear scanning 3D imaging to the sector-scanning, the new imaging method based on a rotated 1D array transducer and limited diffraction beams is developed as follows.

2.1. Array beam

The limited diffraction beam adopted in the proposed method is the array beam [19,20]. The expression for the array beam with parameter k_x, k_y and k_z is

$$\phi_{array}(x, y, z, k) = A(k)e^{jk_x x + jk_y y + jk_z z}, \tag{1}$$

where A(k) is the frequency spectrum of exciting pulse signal and (x, y, z) is the spatial coordinate. The relationship between the wave number k and the frequency f is

$$k = \omega/c = 2\pi f/c, \tag{2}$$

here c is the acoustic speed.

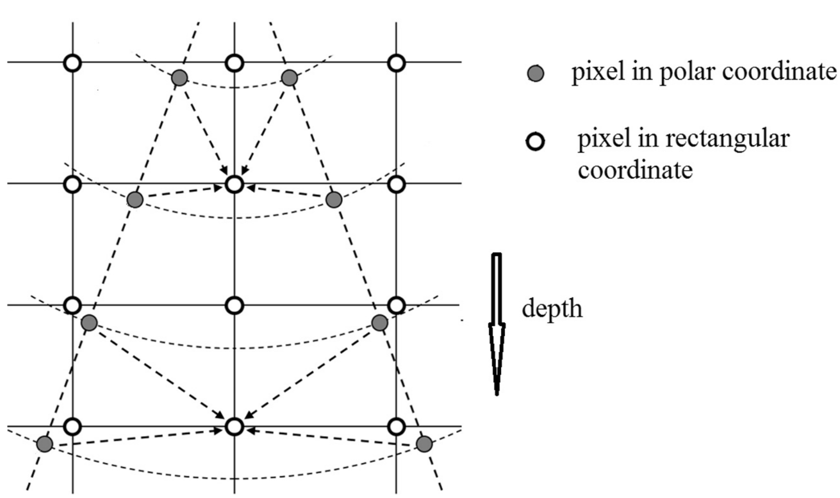

Fig. 1. The conversion diagram in the plane perpendicular to the rotation axis.