

# Ultrasonic Transducers for Medical Volumetric Imaging

Yongrae Roh\*

\*School of Mechanical Engineering, Kyungpook National University

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## Abstract

Three-dimensional ultrasound imaging is a new, exciting technology that allows physicians to use ultrasound to view pathology as a volume, thereby enhancing comprehension of patient anatomy. In this paper, a brief history of the 3-D ultrasound imaging is described in accordance with the development of transducer technology. Then, two representative types of 3-D imaging transducers are reviewed with description of the concept and operation principle of each type: mechanical transducer and matrix array transducer. The mechanical transducer is detailed into free-hand scanning and sequential scanning types. Advantages of each transducer over the other and the technical issues for further performance enhancement are also presented.

**Keywords:** *Ultrasound Transducer, 3-D imaging, mechanical transducer, matrix array* **Subject classification:** *Ultrasound Transducer (4.1)*

## 1. Introduction

The inherent flexibility of ultrasound imaging, its moderate cost, real-time imaging, physiologic measurement, use of nonionizing radiation and no known bio-effects allow the ultrasound diagnosis to have clear advantage over magnetic resonance imaging (MRI) and computerized tomography (CT) [1]. Ultrasound imaging is in routine use in nearly all hospitals and many physician's offices and clinics. Over the past decades, real-time two-dimensional (2-D) ultrasound imaging has made tremendous progress in obtaining important diagnostic information from patients in a rapid, noninvasive manner and has benefitted from significant improvements in image quality and visualization clarity. Although 2-D ultrasound imaging makes it possible for physicians to make important contributions to patient management, advanced technology has permitted volumetric imaging methods to be applied to diagnostic ultrasound by presenting the entire volume in a single image.

Three-dimensional [3-D] ultrasound imaging has ignited interest both in academic communities and commercial industries, offering new opportunities in patient visualization [2-6]. 3-D ultrasound imaging permits better visualization and allows a more accurate diagnosis to be made, thus the volumetric ultrasound images provide the clinician with more confidence in the diagnosis of disease and add knowledge of complex pathology [7, 8]. Major advantages of 3-D ultrasound imaging compared to 2-D ultrasound imaging has been demonstrated as follows; first, volume data can be viewed using a standard anatomic orientation with planar images to obtain simultaneous display of coronal, sagittal and axial planes, in addition to orientations that are difficult or impossible to obtain with conventional 2-D ultrasound imaging due to anatomical constraints (e.g., coronal plane of the uterus). Second, rendering of the entire volume allows the continuity of curved structures, such as liver vessels, the fetal spine or fetal face, to be viewed in a single image. Additionally, by rotating the volume interactively, it is possible to view the structure from multiple orientations or perspectives

Corresponding author: Yongrae Roh (yryong@knu.ac.kr)  
School of Mechanical Engineering, Kyungpook National University  
Sangyeok 3-dong, Buk-gu, Daegu 702-701

that enhance understanding of patient anatomy. Third, more accurate measurement of organ volume and irregularly shaped objects may be readily obtained. Fourth, volume data may be used to guide interventional procedures, providing accurate identification of needle/catheter placement. Fifth, volume data may be archived and subsequently evaluated for further critical review or teaching purposes on site or via the internet after the patient has left the clinic.

Work on 3-D visualization began in the early 1980's. Some basic methods came from the group at Stanford University [9]. Other work came from cardiologists who made efforts to ascertain the volume of cardiac chambers [10]. In the initial stage of 3-D ultrasound imaging, a one-dimensional (1-D) transducer was mounted on an articulated arm where positions of the transducer could be determined by monitoring position sensor signals on the arms. The 1-D array transducer was mechanically moved to provide the 3-D images by sweeping or rotating using either constrained free-hand adapters or an external motion-sensing system. The principle was to stack successive parallel 2-D image sections together with their positional information to compose a 3-D image by a computer [11, 12]. Baba's system used a traditional real-time convex array transducer mounted on the position-sensing arm of a static compound scanner [13]. Another group at the Columbia University led by Donald King developed the method for 3-D spatial registration and display of position and orientation of real-time ultrasound images, which led to the mechanical sequential scanning [14]. The most successful design is the motor-driven array system built into the transducer housing from the Austrian manufacturer Kretztechnik® [15]. In obstetrical and gynecological 3-D imaging, mechanical designs using this sequential scanning method are now a pretty popular choice. Another pioneering work of Feichtinger reported images of 10 weeks embryos imaged with 3-D transvaginal transducers [16].

On the other hand, Smith and his group developed

a matrix array transducer that could image cardiac structures in real-time and 3-D [17, 18]. The matrix array transducer reported in 1997 by the team, which steered the ultrasound beam in three dimensions, contained 2,000 elements in which 512 were used for image formation [19]. The matrix array transducer can be considered a multiple linear connection of 1-D phased array transducers. Due to the relatively small size of the 2-D matrix array transducer, it is more suited to cardiac examination rather than for the abdomen.

The 3-D ultrasound imaging technology has benefitted from increasingly sophisticated computer technology, and system integration has ensured better image quality, data acquisition, analysis and display. However, much of this progress has been derived from the development of the transducers that are in direct contact with patients, which has expanded the possibilities for maximizing patient diagnostic information. As described above, the transducers for current 3-D ultrasound imaging can be grouped into two; mechanical transducer and matrix array transducer. This paper reviews the transducer technology for the 3-D ultrasound imaging with particular emphasis on the operation principle and structure of the mechanical and matrix array transducers.

## II. Mechanical Transducer

In general, current 3-D sonographic imaging systems are based on 1-D (either linear or curved) or annular array transducers whose position is accurately monitored by a position-sensing device. Figure 1 is the schematic structure of a typical 1-D linear array transducer. There are several tens or hundreds of piezoelectric elements arrayed in a linear fashion and the whole elements are fired simultaneously or in sequence to get a 2-D planar image as illustrated in Fig. 2 [1]. Due to the inherent 1-D nature of the array, either linear or curved, the transducer can acquire only the 2-D images. Mechanical transducers

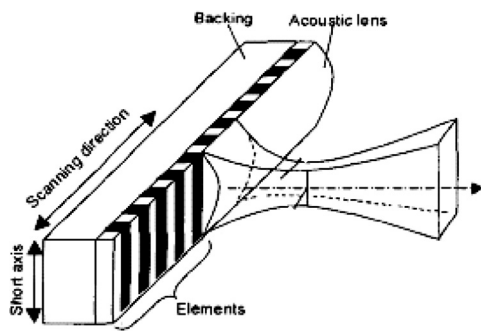


Fig. 1. Schematic structure of a typical 1-D linear array transducer.



Fig. 2. 2-D ultrasound image acquired by a 1-D array transducer [1].



Fig. 3. 3-D image acquired by a 3-D ultrasound imaging transducer [20].

are using this 1-D array transducer to compose a 3-D image illustrated in Fig. 3 by combining the 2-D images with the information on the position of the 1-D array [20]. Position data may be obtained from an external positioning system in the examination room or stepping motors inside the transducer. During ultrasound imaging signal acquisition, images and position data are stored in a computer for subsequent projection into a volume data set. Depending on the type of acquisition used, the acquisition slices may be in the pattern of a series

of parallel slices, rotation around a central axis of the image, or a fan-like rotation around a transverse axis.

There are two different main approaches to obtain a 3-D ultrasound data set. The first approach tracks the motion of an ultrasound transducer in space, which requires external “space-tracking” technology; this method is often referred to as random or free-hand scanning. The second approach uses internal position sensing devices installed inside the transducer and the transducer motion follows a pre-defined profile, which is named mechanical sequential scanning.

## 2.1. Free-hand scanning

In this free-hand scanning, a sonographer holds the 1-D array transducer and manipulates it in the usual manner over a target, e.g. human body to be viewed. Multiple 2-D images are acquired at arbitrary positions and angles according to the control of the sonographer. Then all the 2-D images each with corresponding transducer position and angle information are combined and processed to compose a 3-D image. This approach uses a position sensor device attached to the transducer that simultaneously determines the position and orientation of the transducer. A variety of position-sensing devices have been used to obtain position data [5]. Three representative types of the devices used in practice are (1) an acoustic sensor that sends regularly an acoustic pulse to be detected by a fixed microphone system in the examination room [21], (2) a mechanical articulated arm whose displacement can be identified as in usual robot arms [22], and (3) an electromagnetic sensor attached to the transducer that continuously monitors the transducer position in space [23]. Figure 4 illustrates the three positioning methods.

The acoustic sensor and the mechanical articulated arm methods were not given a favorable attention in clinical environment as opposed to the electromagnetic location system. The free-hand acquisition method was, until recently, mostly used in the field of obstetrics

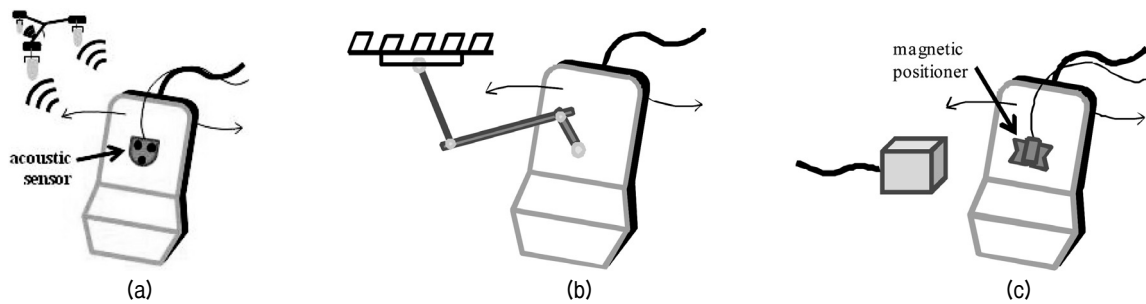


Fig. 4. Schematic diagram showing the positioning methods for free-hand scanning: (a) acoustic sensor, (b) articulated arm, and (c) electromagnetic positioner.

and gynecology, and considered not useful for cardiology because of acquisition problems and insufficient sampling resolution. Although the free hand scanning method offers good flexibility, the problems inherent to the free-hand scanning such as positioning inaccuracy and irregular scanning due to the hand-held manipulation are likely to reduce image quality, especially when imaging small structures.

## 2.2. Mechanical sequential scanning

The problems with the free hand scanning can be avoided by mechanically moving the 1-D array transducer in a precise and predefined manner. As the transducer is moved, 2-D ultrasonic images are collected at predefined spatial intervals so that the imaging sequence acquires the volume of interest without missing any regions. A number of investigators and commercial companies have developed different sorts of mechanical sequential scanning transducers [20, 24–31]. In general, these transducers make use of conventional 1-D linear or convex array transducers mounted in a mechanical mechanism that allows translation or rotation of the 1-D array transducer. In most cases, this method integrates the position-sensing system within the transducer housing. Since the positioning system is implemented within the transducer, the transducer tends to be relatively larger than standard 1-D array transducers, but it eliminates most of the issues related to external position sensors needed for the free-hand scanning with respect to calibration and accuracy.

The mechanical sequential scanning system has

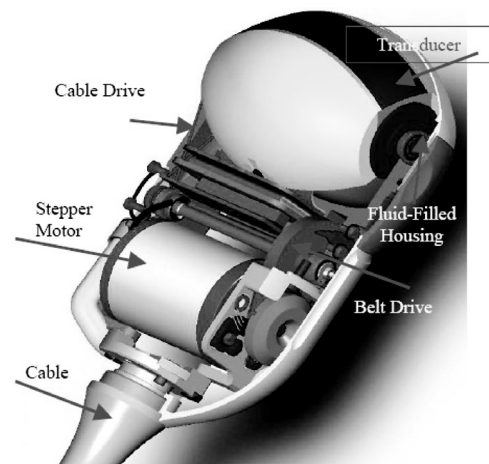


Fig. 5. Representative structure of a mechanical sequential scanning transducer for 3-D ultrasound imaging [23].

the capability of controlling a servo or stepping motor that is able to accurately manipulate the position of a transducer. Figure 5 is a schematic structure of a representative mechanical sequential scanning transducer [20]. The stepping-motor is commanded by a steering logic within an observer-selected range of angle. This permits optimal temporal and spatial registration of the ultrasound images. As illustrated in Fig. 6, after a specific angle is selected by the steering logic, a 2-D ultrasound image is sampled, digitized and stored in memory [28]. Then, the transducer plane is moved to the next location, and another 2-D image is acquired. As a result, the relative angle between the 2-D images is exactly known, eliminating distortion in the resultant scan. For high quality images, the motor should be precisely controlled for the 1-D array transducer to accurately follow a desired motion profile as illustrated

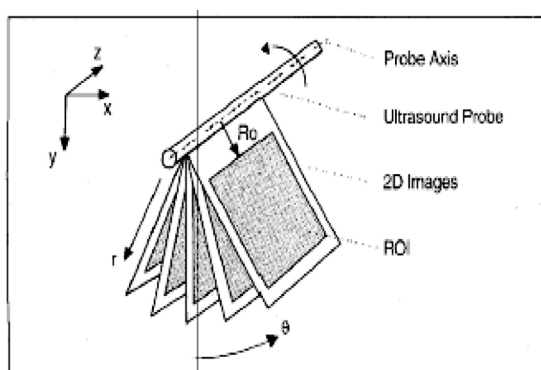


Fig. 6. Schematic diagram of acquiring multiple 2-D images by mechanical sequential scanning [28].

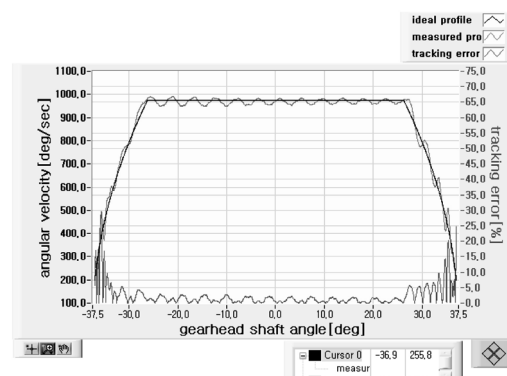


Fig. 7. Motion profile of the mechanical sequential scanning transducer for 3-D ultrasound imaging; straight line is a desired profile while the wrinkled line is a measured profile of the array [30].

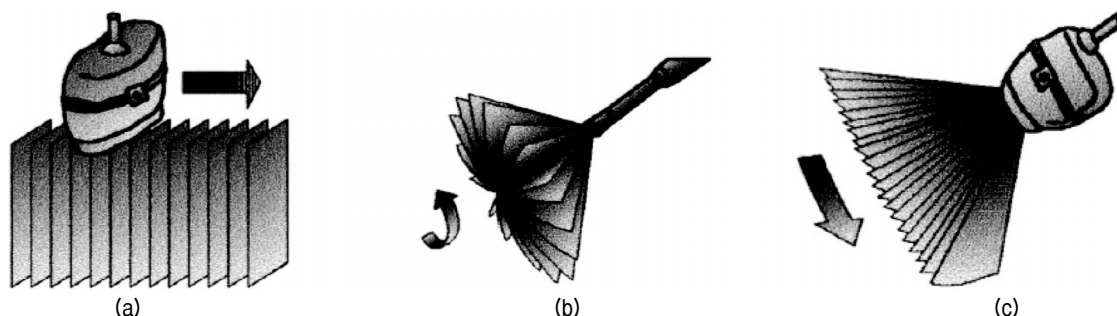


Fig. 8. Different types of mechanical sequential scanning: (a) linear scanning, (b) rotational scanning, (c) fan-like scanning [32].

in Fig. 7. Figure 8 describes the three representative ways to control the motor, eventually the 1-D array transducer, when using this sequential imaging technique: (1) Linear, parallel equidistantly spaced images can be collected by computer-controlled movement in a linear direction [29], (2) Rotational, the transducer is rotated in a semicircle of  $180^\circ$  around the central axis of the image plane, which results in a conical volume data set [27], and (3) Fan-like, a pyramidal data set can be obtained by moving the ultrasound transducer in a fan-like arc at prescribed angles [30]. When the scanning process covers the whole range of angle by the predetermined interval, all the 2-D images are combined and processed to construct a 3-D image by the surface rendering technique.

These mechanical sequential scanning transducers have been produced for both transabdominal and intracavitary diagnoses, and are becoming more and more popular these days [32]. The technical issues

concerning higher performance with these transducers are a higher scanning rate (wobbling rate), a larger scanning angle (field of view), and better long-term reliability and compliance. For vivid 3-D imaging, sonographers always desire a higher scanning rate over a wider field of view. However, the very fundamental limitation in scanning with these mechanical transducers is that the 3-D image rendering process can not start until the transducer acquires all the needed (usually several tens of) 2-D images to compose the 3-D image. The acquisition time is typically in the order of several hundred milli-seconds. Hence, the 3-D images from the mechanical transducers can not be true real-time images. Further, the crucial concern in designing and manufacturing these transducers is to maintain the exact mechanical motion of the driving mechanism inside the transducer for long term usage [30]. Since the mechanism to operate the transducer is a mechanical device made of metal or plastic components, abrasion and heat

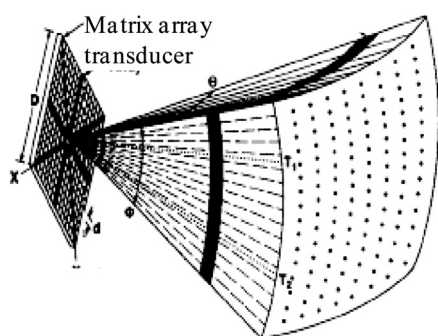


Fig. 9. Principle of volumetric imaging with an ultrasonic matrix array transducer [18].

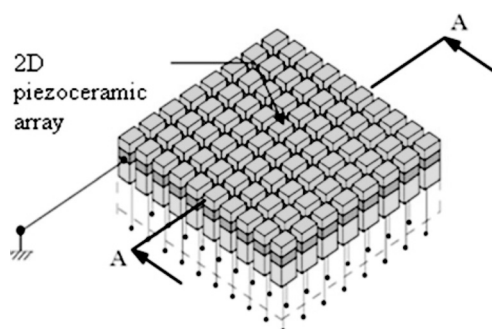


Fig. 10. Schematic structure of a matrix array transducer for 3-D ultrasound imaging.

accumulation inside the transducer is unavoidable, which may deteriorate the quality of the scanning over time.

### III. Matrix Array Transducer

The techniques described above use 2-D images generated by conventional 1-D array transducers. Information about the third dimension is achieved by physical movement of the 1-D array transducer, either using mechanical means or by the hand of the operator. The ideal, but technically the most challenging, direction is to have real-time 3-D images available immediately when the ultrasound examination is being performed. A different approach to realize true real-time 3-D ultrasound images is the one shown schematically in Fig. 9. Information about the third dimension is achieved by replacing physical movement of the array transducer with electronic scanning over a plane. In this approach, the 2-D array transducer called a matrix array transducer generates a pulse

of ultrasound diverging away from the array in a pyramidal shape. The echoes are processed to generate 3-D information in real-time. These types of transducer will allow real-time echo-cardiographic 3-D imaging [10]. A real-time volumetric ultrasound imaging system with this matrix array transducer has been developed at Duke University [17, 18] in which the elements are arranged in a 2-D grid. Figure 10 shows a schematic structure of the matrix array transducer. After transmission of the sound pulse into a wide-angle cone volume by parallel processing, a multiplicity of receiving sound beams allows sampling the volume at one shot. The integrated images are true real-time 3-D ultrasound images.

For high resolution of the 3-D image, a lot of elements are required to be installed in the matrix normally in the order of several thousands compared with several hundreds in conventional 1-D array transducer. Presently, for piezoelectric transducers, an approximately 2,500 element matrix array transducer has been commercialized [25], and efforts are being made to further increase the number of the active elements [33]. The cMUT (capacitive micromachined ultrasound transducer) matrix array transducer developed at Stanford University has been reported to include as many as 16,382 ( $128 \times 128$ ) elements [34, 35].

Although the ultimate expectation is that this matrix array transducer will replace integrated mechanical scanning transducers and other position-sensing systems, matrix array transducer is still a developing technology. Thus far, 3-D ultrasound imaging systems utilizing matrix array transducers have been used to obtain simultaneous planes from the volume, rather than acquiring the entire volume [32]. A significant issue to be resolved in the electronics side is the data bandwidth required for real-time volume acquisition. Although multiple parallel channels can be used, issues of interference and computing/storage bandwidth still need to be resolved. 2-D array transducers are relatively small (less than 4 cm square) and, as a result, their field of view may

also be relatively small. In the transducer side, the huge number of elements in the matrix array transducer inhibits the use of conventional dicing and wiring technology. Much more fine and precise material processing and fabrication or MEMS (micro-electro-mechanical system) technology is essential. In addition, the close spacing between the active elements in Fig. 10 causes severe cross-coupling between the elements. The cross-talk normally increases in proportion to the number of elements [33], and the cross-talk can change the beam pattern and sensitivity of the transducer. In order to reduce the level of the cross-talk, it may be a must to install minor kerfs between the existing major kerfs of the matrix array, which actually quadruples the number of elements to be implemented in the array.

#### IV. Conclusions

In this paper, the concept and principle of 3-D ultrasound imaging transducer technology were reviewed by describing mechanical transducers and matrix array transducers. 3-D ultrasound imaging is a new, exciting technology that allows physicians to use ultrasound to view anatomy and pathology as a volume, thereby enhancing comprehension of patient anatomy. On-going developments in computers and signal processing technology now permit acquisition, analysis and display of volume data in seconds, facilitating many opportunities for rapid diagnosis and interventional techniques. Both commercial and academic interest in 3-D ultrasound imaging is mounting and persistent advancements and improved understanding are expected in the near future. Continuing development of transducer technology is playing a key role in enhancing the 3-D imaging performance to replace current 2-D sonography by providing real-time capability and interactivity. It is expected that 3-D ultrasound imaging will be a routine part of patient diagnosis and management in the future.

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## **[Profile]**

### **• Yongrae Roh**

Received his B.S. and M.S. degrees from Seoul National University, Korea, in 1984 and 1986, respectively. He got his Ph.D. from Pennsylvania State University, U.S.A., in 1990. He worked in the Research Institute of Industrial Science & Technology, Korea, as a senior research scientist. In 1994, he joined Kyungpook National University, Korea, and now is a professor in the School of Mechanical Engineering. His major research area is the development of piezoelectric devices and ultrasonic transducers. He has authored more than 180 scientific journal papers, and holds 28 domestic and international patents.