CHAPTER 7

TRANSDUCERS FOR REAL-TIME IMAGING

The concept of real-time ultrasound was introduced in Chapter 6. Essentially, it involves the generation of images of the same cross-section repetitively and at a rate high enough to create the impression of continuity of events in time. This facilitates the observation of motion in any part of the subject within the cross-section being scanned. The images are generated and erased in rapid succession at rates exceeding about 25 frames per second. The observer simultaneously views the sequence of images, but is unable to resolve them in time, thus the motion picture effect is created. When a permanent record is desired, the image at the particular moment is held still, or "frozen", and a hard copy of it recorded (freeze frame). Capturing a record without freezing would cause motional blurring of the captured image.

In order to achieve the high framing rates required in real-time imaging, it is necessary to cause the ultrasound beam to sweep across the section of interest in the subject very rapidly and repetitively. This is the main challenge in the design of equipment for real-time imaging. The transducer and the electronics must be suitably adapted to meet the special demands for high framing rates.

7.1 Transducer design

Transducers for real-time imaging may be classified broadly into two categories: mechanical transducers and electronic transducers. In mechanical transducers, the beam sweep is achieved through physical movement of some part of the transducer, usually the crystal element(s), whereas in electronic transducers the beam is swept by electronic activation of crystal elements, without causing the transducer to move physically.
7.1.1 Mechanical transducers

Mechanical transducers are made using either a single piezoelectric crystal or a small group of crystals. A single crystal element may be rocked to perform pendulum motion through a suitable angle. The motion is effected using an electric motor. The angle of swing will define the field of view (see Fig 7.1). The image is triangular in shape and is referred to as a sector scan. Each swing of the crystal produces one image frame, and the frame rate is equal to the number of swings per second.

![Diagram of mechanical transducer with single crystal element performing pendulum motion.](image)

Fig 7.1 Mechanical transducer with a single crystal element performing pendulum motion

Alternatively, the crystal can be driven linearly along the scan section to perform rapid to-and-fro motion. The field of view in this case will be rectangular. Another strategy that has been used with single crystal transducers is to employ an oscillating mirror to swing the beam from a stationary crystal by reflection.

The most common method used in mechanical transducers employs a small group of crystal elements (typically 3 or 4 crystals) mounted symmetrically on a rotating wheel. The wheel is driven by an electric motor to perform circular motion in one direction only. The crystal elements are excited one at a time to provide the ultrasound beam. Each crystal is activated to transmit and receive only as it moves through a predetermined arc.
which may be referred to as the **active sector**. Outside this arc, the crystals remain inactive. Only one crystal may be active at any given moment. An example of this configuration is illustrated in Figure 7.2.

![Diagram](image)

**Fig 7.2 Mechanical sector scanner with four rotating crystal elements**

For each complete rotation of the wheel, the number of image frames generated will be equal to the number of crystal elements constituting the transducer. The frame rate will further be influenced by the speed of wheel rotation. For example a transducer with 4 crystals performing 10 revolutions per second will produce real-time images at a rate of 40 frames per second.

Since the instantaneous beam is provided by one crystal at a time, the crystal diameters must be appropriately chosen to provide a suitable beam shape (see Chapter 4). Beam shape can further be influenced by focusing. Mechanical transducers employ fixed focusing methods.

At the high speeds used to move the crystal elements, direct contact between the crystals and the patient’s skin would be impractical and uncomfortable to both the patient and the operator. To avoid contact scanning, the crystals are housed in a small oil-filled
bath. This measure introduces other advantages as well: the oil lubricates the moving parts, the field of view near the skin is improved, and some near field artefacts are transferred from regions of anatomical interest (on the image) to the region of the liquid path (see Chapter 8). Although the ultrasound beam will have to transverse some additional distance across the oil path, beam attenuation is not a major concern because the liquid bath is essentially an acoustic window (see Chapter 3).

7.1.2 Electronic transducers

Electronic transducers are made from a large number of small, identical crystal elements which are acoustically insulated from each other. The crystals are arranged in a suitable geometrical configuration, or an array, to provide the desired field of view. Movement of the beam is effected by exciting the crystal elements in an orderly fashion without having to move the transducer physically. The crystal elements may be pulsed individually, one at a time, to provide the instantaneous beam, a pulsing procedure known as sequential pulsing. Alternatively, the instantaneous beam may be provided by a small group of crystals excited together. The group is a segment of the array, and such group pulsing is called segmental pulsing. The choice between sequential and segmental pulsing is dictated by the need to provide a suitable beam shape that optimizes the conflicting interests of a narrow beam to enhance spatial resolution, on the one hand, and a sufficiently long Fresnel zone that allows for adequate tissue depths to be investigated, on the other hand. In a multcrystal transducer with very many crystal elements, the crystals will, of necessity, be small in size, otherwise the transducer would be too large and bulky. It will be recalled that a small source of ultrasound produces an unsatisfactory beam shape, a short Fresnel zone and rapid divergence in the far field (see Chapter 3). Sequential pulsing of very small crystal elements would therefore give a poor beam pattern. To avoid this problem, segmental pulsing may be employed: a small number of adjacent crystals are excited together as a group to provide the instantaneous beam. Each pulse of ultrasound from this group results in one scan line. The number of crystal elements constituting the group is chosen such that the resulting beam shape will be similar to that from a transducer in which crystals are pulsed individually. (The crystal elements in transducers employing sequential pulsing must be of adequate dimensions to provide a suitable beam shape).
The stepwise shift in the beam sweep across the length of the array is important because it affects the interplay between various image characteristics (see Chapter 8). It is appropriate here to consider this beam shift in relation to the number of scan lines contributing to the image frame, and how this affects the pulsing procedure in the segmental pulsing of multicrystal transducers.

In sequential pulsing, each crystal element generates a scan line on its own. Thus, a transducer with 60 crystal elements will generate an image frame from 60 scan lines. The number of scan lines contributing to the image affects spatial resolution in the direction of the length of the array (lateral resolution). The larger the number of scan lines, the better the lateral resolution. In segmental pulsing, if the groups of crystals were chosen independently and exclusively of each other, the number of scan lines in one sweep of the beam across the array would be much reduced, in relation to the total number of crystal elements in the array. For example, segmenting an array of 100 crystal elements into independent groups of 5 would produce an image frame from 20 scan lines, as compared to 100 scan lines if the same array were pulsed sequentially (we recall, though, that the groups of 5 provide a more practical beam shape). In order to combine the advantages of a suitable beam shape and those of generating the image frame from a large number of scan lines, segmental pulsing is done by sweeping the beam electronically in small steps across the crystal array, by overlapping the sets of crystals instead of grouping them in mutually exclusive segments. We consider the example of a transducer with 100 crystal elements segmented into groups of 5 as the beam is swept from the first to the 100th element. The first scan line is provided by pulsing crystal numbers 1 - 5, the second scan line by crystals 2 - 6, the third by numbers 3 - 7, and so on. The last scan line will come from crystal numbers 96 - 100. In this manner, the shift in the beam sweep is effected in small steps (the lateral shift is equal to the length of one crystal element along the direction of the array), giving rise to a large number of scan lines: a total of 96 in this example. At the same time, the advantages of a large source of ultrasound (the dimensions of 5 crystal elements) are retained.
7.1.2.1 Geometry of multi crystal arrays

Different geometrical configurations have been used in multicrystal arrays. In **linear array transducers**, the crystal elements are arranged in a row. They may be activated either sequentially or segmental. They generate rectangular fields of view (see Fig. 7.3), associated with good visualization of superficial regions.

![Diagram showing linear array transducer](image)

**Fig 7.3** Linear array transducer

In an **annular array transducer**, the crystal elements are arranged in concentric rings. For electronic beam sweep, the set of typically 5 - 10 ring elements is pulsed sequentially to move the beam from the innermost ring outwards. The beam can also be moved mechanically by oscillating the whole assembly from side to side, or by reflecting the beam from a moving acoustic mirror.

A **phased array** system may have the same geometrical configuration as either a linear array or an annular array, but the procedure of activating the crystal elements is different. Neither sequential nor segmental pulsing is employed. In phased array transducers, all the crystal elements are pulsed almost instantaneously as one group, excepting for very short time delays between the activations of individual crystal elements. The carefully controlled electronic time delays are programmed into the pulsing of each crystal element to facilitate movement and focusing of the beam (see section on electronic beam focusing...
in this Chapter). For each pulsing of the array, a phased array system produces only one "scan line" over the whole area of the array. The number of scan lines contributing to the image is increased by sweeping the beam electronically through different directions using the short time delays.

7.1.2.2 Electronic beam focusing

Mechanical systems for focusing the ultrasound beam have been considered in Chapter 5. Transducers for real-time imaging employ some of these mechanical methods, but more significantly they use electronic methods to steer and shape the beam.

Electronic beam focusing relies on the application of very short delays in the pulsing of individual crystal elements within the array to facilitate in-phase arrival of wave fronts from the different elements at the desired focal point. The duration of the time delay for beam focusing is comparatively much shorter than the interval between the pulsing of crystals (or groups of crystals) that is required to gather information and then move the beam to the next line of search across the transducer array. During data collection, time must be allowed for the pulsing of the crystal(s), for the ultrasound beam to travel to the desired tissue depth and back, and for the transducer to detect the returning echo signal. Typically, this sequence of events may take some microseconds ($10^6$s) to gather information for one scan line. By comparison, the delay times employed in electronic beam focusing are of the order of nanoseconds ($10^9$s).

Figure 7.4 illustrates a time delay procedure that may be used in the segmental pulsing of a group of 5 crystal elements in order to produce a focal point at F. Outer elements are excited earlier than inner ones in such a manner that wave fronts from all the crystals will arrive in phase at the chosen focal point.
First, the peripheral crystals 1 and 5 are excited. Ultrasound from these two crystals will travel the longest distance to reach the central axis of the beam produced by the group. After an appropriate time interval, crystals 2 and 4 are excited next. A short delay follows before crystal 3 is fired. The time delays are carefully controlled by electronic circuits to ensure that contributions from all the five crystals in the group will arrive at F in phase to reinforce each other and produce a high intensity zone. The focus can be changed by altering the time delay programme. Variable focal depth is a major advantage of electronic focusing over fixed, mechanical focusing.

7.1.3 Special applications transducers

Some transducers are designed to be used in special applications. This requires that they be specially adapted for the particular tasks. Parameters for special adaptation may include transducer size and/or shape, provision of particular ranges of beam frequency, or some desirable beam focusing capabilities. Examples of such special applications transducers include intra-cavitary probes, cardiac probes, Doppler probes, and high resolution small parts transducers. The reader is referred to specialized articles for further details.