Summary. Volumetric cardiac ultrasound imaging has steadily evolved over the last 20 years from an electrocardiography (ECC) gated imaging technique to a true real-time imaging modality. Although the clinical use of echocardiography is still to a large extent based on conventional 2D ultrasound imaging it can be anticipated that the further developments in image quality, data visualization and interaction and image quantification of three-dimensional cardiac ultrasound will gradually make volumetric ultrasound the modality of choice. In this chapter, an overview is given of the technological developments that allow for volumetric imaging of the beating heart by ultrasound.

3.1 The Role of Ultrasound in Clinical Cardiology

Ultrasound (US) imaging is the modality of choice when diagnosing heart disease. This is due to fact that it is non-invasive; does not show adverse biological effects; has an excellent temporal resolution; is portable (and can thus be applied bed-side) and is relatively cheap when compared to other imaging modalities. As such, US imaging has become an indispensable tool for daily management of cardiac patients.

Historically, cardiac ultrasound started with acquiring a single image line as a function of time, which is referred to as motion mode (M-mode). It allowed studying basic morphological properties of the heart such as estimating the dimension of the left ventricular cavity or the segmental wall thickness. In addition, the motion of the heart during the cardiac cycle could be monitored which can give information on cardiac performance. However, as the field-of-view of this imaging approach remained very limited, correct navigation through the heart and interpretation of the recordings was difficult.

Hereto, two-dimensional (2D) ultrasound imaging (brightness mode (B-mode)) was introduced by mechanically moving (i.e., tilting), the transducer between subsequent line acquisitions. This mechanical motion of the transducer was replaced by electronic beam steering in the late sixties when phased array transducer technology was introduced. As such, cross-sectional
images of the heart could be produced in real-time at typical frame rates of about 30 Hz. Although continuous improvements in image quality and image resolution were obtained in the following decades, imaging a 2D cross-section of a complex 3D organ such as the heart continued to have intrinsic pitfalls. As such, three-dimensional (3D) US imaging of the heart has been a topic of research for several decades.

3.2 Principles of Ultrasound Image Formation

The fundamental principle of echocardiography is relatively simple: an US pulse is transmitted into the tissue and the reflections that occur while the wave propagates (due to local inhomogeneities in mass density or regional elasticity) are detected by the same transducer as a function of time. As the velocity of sound in tissue is known, the time at which a reflection is detected and the distance at which this reflection took place are linearly related. As such, the reflected signal can be used to reconstruct a single line in the ultrasound image giving information on the tissue reflectivity (i.e., its acoustic properties) as a function of depth. In order to generate a 2D or 3D image, the above measurement is repeated by transmitting ultrasound in different directions either by mechanically translating/tilting the transducer or by electronic beam steering.

3.2.1 The Pulse-Echo Measurement

The basic measurement of an ultrasound device can shortly be summarized as follows:

1. A short electric pulse is applied to a piezoelectric crystal. This electric field re-orient the (polar) molecules of the crystal and results in a change of its shape. The crystal will thus deform.
2. The sudden deformation of the piezoelectric crystal induces a local compression of the tissue with which the crystal is in contact (Fig. 3.1a).
3. This local compression will propagate away from the piezoelectric crystal (Fig. 3.1b). This compression wave (i.e., the acoustic wave) travels at a speed of approximately 1,530 m/s in soft tissue through the interaction of tissue elasticity and inertia. Indeed, a local compression is counteracted upon by the tissue elasticity which results in a return to equilibrium. However, due to inertia, this return to equilibrium is too large resulting in a local rarefaction (i.e., de-compression), which in turn is counteracted upon by tissue elasticity. After a few iterations, depending on the tissue characteristics and of the initial compression, equilibrium is reached since each iteration is accompanied by damping, i.e., attenuation. The rate of compression/decompression determines the frequency of the wave and is typically 2.5–8 MHz for diagnostic ultrasound imaging. As these frequencies cannot be perceived by the human ear, these waves are said to