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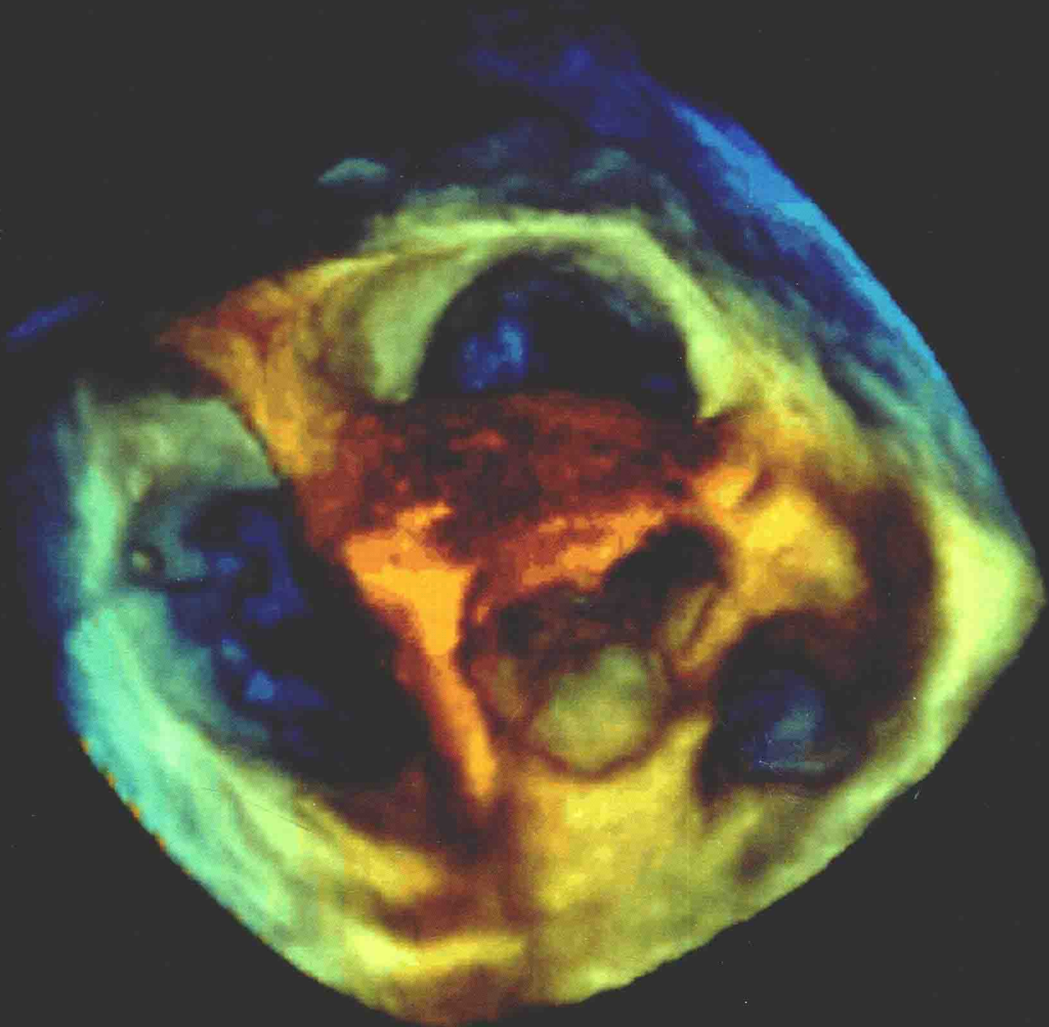
3D ECHOCARDIOGRAPHY



Edward A. Gill

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ATLAS OF 3D ECHOCARDIOGRAPHY

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DEDICATION

To my late friend James E. Weiel, PhD, who died suddenly and unexpectedly of cardiac causes during Thanksgiving week 2011, and whose unrelenting dedication to his two passions of science and photography was unequaled.

Preface

Three-dimensional (3D) echocardiography has arguably been the most significant development for echocardiography in the past two decades and has been very important for the development of cardiology in general. When I was a medical resident in the late 1980s, echocardiography inspired me to pursue a fellowship in cardiology. The reason was clear: no technology at that time allowed such complete evaluation of cardiac structure and function and displayed it in such an exquisite fashion. Fast forward to today, and this opinion hasn't changed; echocardiography never fails to advance its technology and organize it in such an eye-pleasing fashion. 3D echocardiography is the flagship example. When the first versions of 3D echocardiography began to enter the clinical cardiology market in the early 1990s, it was clear to me that I wanted this technology for our echocardiography laboratory. Since the early gated transthoracic 3D transesophageal echocardiography acquisition in 1995 and on to real-time transthoracic 3D in 2002 and real-time transesophageal 3D in 2007, I have been particularly privileged to help with the development and feedback of this technology and ultimately to institute it in everyday clinical use. *Atlas of 3D Echocardiography* is the culmination of years of work applying 3D technology to thousands of interesting clinical cases. I believe this atlas will enable readers to greatly enhance their understanding and appreciation of 3D echocardiography.

Edward A. Gill

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I acknowledge the tireless efforts of the contributing authors who, by sharing their expertise and experience, have made this project complete. I also thank Carla Griswold, my administrative assistant, for her expertise and dedication with the preparation of all manuscripts, figures, references, and additional material. I thank all of the Harborview Medical Center cardiac sonographers for helping capture images for this book: Elenese Berther, Alicia Bourne, Rachel Karl, Denise McRee, Eric Sisk, and Terese Tognazzi-Evans. Special thanks to all the administrators at Harborview Medical Center who supported the development of three-dimensional echocardiography at our institution. Finally, but most importantly, I thank my parents, without whose support medical school would have been only a dream, let alone writing this book. Thanks also to my immediate family—my wife, Kathy, and our two sons, Matt and Marcus—for their unending love, support, and most of all, patience with this project.

Foreword

On October 29, 1953, Inge Edler, inspired by the use of radar technology in World War II, recorded the first "ultrasound cardiogram" and published his group's findings 1 year later. Since then, the technology of echocardiography has never failed to progress and excite. Just when echocardiography is deemed mature, a noteworthy breakthrough emerges. To say that real-time three-dimensional echocardiography (RT3DE) was such a breakthrough is, realistically, a major understatement. RT3DE, as it emerged in the transthoracic version in 2002, followed by the transesophageal version in 2007, is arguably the most important technologic breakthrough for cardiology to date in the twenty-first century. From a cultural standpoint, it is so timely that its development and introduction coincide with the beginning of Generation AO, the "always on" generation.

It was exceedingly important for echocardiography to develop a clinically useful 3D technique because other cardiac imaging modalities, notably cardiac magnetic resonance imaging and, to a greater extent, computed tomography, also have the ability to display information in three dimensions. However, the two unique aspects of RT3DE are the ability to display in real time and the clear superiority of valvular visualization, particularly mitral valve visualization by RT3D transesophageal echocardiography (TEE).

RT3DE is now a technology that is appreciated for its benefits worldwide. It has been interesting to see RT3DE flourish to a somewhat greater extent in Europe and Asia than in the United States, at least partly due to economic barriers for the institution of new imaging technology in the latter.

In this atlas, Dr. Gill and his coauthors have brought 3DE to life in a comprehensive publication that will serve as an indispensable learning tool for the novice as well as the expert in 3DE. Dr. Gill has covered everything from the technology and history of 3DE to the basic examination and its advanced uses, including the use of RT3DTEE in interventional procedures. Indeed, 3DE has evolved dramatically. It has gone from a novelty that produced intriguing and awe-inspiring pictures to a technology that is absolutely essential for some advanced interventional procedures, notably procedures that involve manipulation of the mitral valve—such as placing mitral clips and positioning vascular plugs to occlude periprosthetic regurgitation.

Bernhard Mumm
Roberto M. Lang, MD
September 2012

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CHAPTER 1

Historical Perspective on Three-Dimensional Echocardiography

Edward A. Gill and Berthold Klas

INTRODUCTION

Three-dimensional echocardiography (3DE) has been in existence since the 1970s, albeit with images that barely resembled a heart at that time. Throughout the 1970s and 1980s, 3DE was limited by computing power, both at the workstation and at the ultrasound level. In the 1990s, as both two-dimensional echocardiography (2DE) image quality and computing power dramatically improved, 3DE began to make strides as a possible clinical entity. During these early attempts at 3DE, it was never real time and was approached from the perspective of capturing multiple 2D images of the heart and either tracing a wire frame of the heart or melding the 2D images together using interpolation methods to create a 3D image. The first attempts at real-time 3DE were undertaken by von Ramm et al at Duke University in the 1990s. The major transition from research to clinical tool for 3DE happened in 2002 when the first reasonably user-friendly version of real-time 3DE (RT3DE) was introduced. This was also the first version of RT3DE to have diagnostic-quality 3DE images performed by an ultrasound system that was capable of both 2DE and 3DE.

EARLIEST APPROACHES

3DE had its beginnings in the 1970s with primitive equipment and equally primitive images. By the mid-1980s, there was early 3DE performed with standard B-mode ultrasound and tracking devices designed to locate the transducer in space. The initial approach to 3D echo was to obtain multiple 2D images and reconstruct them into a 3D image. This was accomplished by registering the 2D images such that it could be discerned how the individual images fit together to form the 3D image. Such registration of the images was achieved by tracking the transducer in space via mechanical, acoustic, electromagnetic, or optical detection apparatus. In the mechanical approach, the transducer had an actual mechanical arm attached to it and therefore dictated movement in space (**Figure 1-1**). Dekker and colleagues[1] are credited with this first iteration of 3DE using the mechanical arm approach in 1974. Next came an acoustic attempt at location, the "spark gap" technique by Moritz and Shreve[2] in 1976. In this technique, the transducer was located by sending pulsed acoustic signals from a device holding the transducer, called a spark gap to a Cartesian locator grid (**Figure 1-2**). This approach, in theory, allowed free-hand scanning—meaning that the transducer did not have to follow a predetermined pathway and, indeed, was the precursor to free-hand scanning using an electromagnetic locator. Both electrocardiography and respiratory gating were often used, or images were acquired with breath holding. Initially, only end-diastolic and end-systolic images of the left ventricle (LV) were obtained. Over time, complete cardiac cycles could be obtained.[3,4] Several groups published articles during this period using a variety of primitive transducer tracking systems and the resultant less than pleasing 3D imaging.[5-10]

In 1977, Raab and colleagues[11] developed the magnetic locator, which ultimately led to the most advanced type of free-hand scanning, but this method for transducer location never

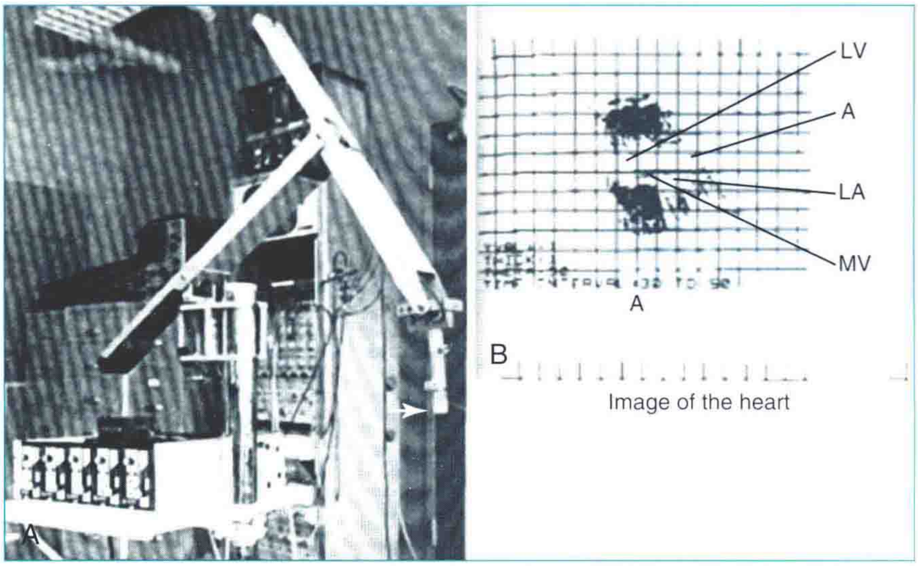

Figure 1-1 **A,** The mechanical arm used by Dekker and colleagues[1] for tracking the ultrasound transducer in space. Note the *arrow* depicting the actual ultrasound transducer. As might be imagined, this apparatus was not well received by sonographers because moving the transducer around was physically taxing, given the weight and awkwardness of the mechanical arm. **B,** Image of the heart. Note that the image shows only mild resemblance to the actual heart and heart chambers. A, aorta; LA, left atrium; LV, left ventricle; MV, mitral valve.

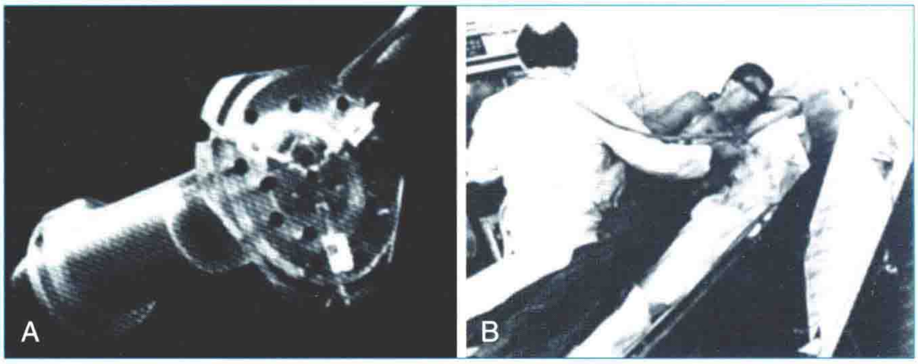

Figure 1-2 An acoustic "spark gap" apparatus used by Moritz and Shreve[2] for locating the transducer for three-dimensional echocardiography. **A,** Actual device housing the transducer, with the audio signal sent from the trifurcating mechanism. **B,** The device in practice, with the coordinates shown on the board to the right of the user.

caught on until the mid-1990s. This method is still used today by some labs, predominantly for research purposes (**Figure 1-3**; see also Figures 1-13, 1-14).

In between the spark gap and the free-hand magnetic approaches were myriad tactics that used the technique of transducer movement in a preprogrammed, stepwise fashion while attempting to keep the patient and the sonographer as stationary as possible. The mechanical devices then moved the transducer in a linear, fanlike, or rotational direction. An example of a fanlike acquisition is shown in **Figure 1-4**.

Fanlike Scanning

Fanlike scanning was, in theory, advantageous for evaluating the right ventricle (RV) compared with rotational or linear scanning, since the RV is not easily accessed from the apex and often is best imaged from the RV inflow tract using a more rightward direction of scanning from the standard parasternal view.[12]

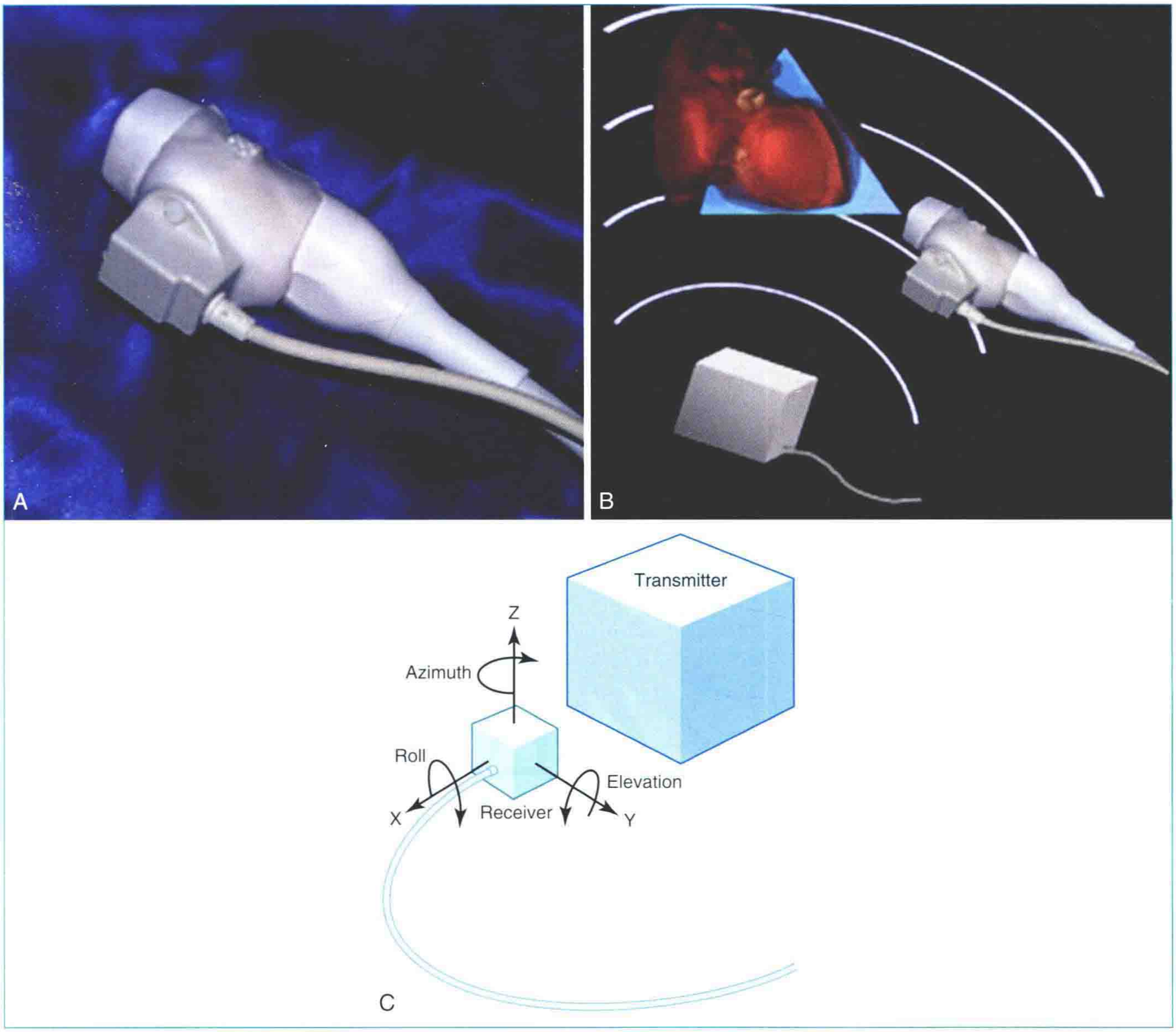

Figure 1-3 **A,** Electromagnetic locator device. The sensor is shown attached to a holder for the transducer. **B,** Summary of the electromagnetic sensor system. The magnet is located in the box, which serves as the transmitter. The magnet is connected to the sensor and indirectly to the ultrasound system. **C,** The location of the transducer is tracked by the electromagnetic sensor.

Rotational Scanning

The rotational approach used a cylinder-like mechanical apparatus that those in the industry at that time referred to as the "bazooka" (**Figure 1-5**). This device had a mechanical stepper motor that moved the transducer sequentially through a semicircular or 180-degree scan with stops every two to three degrees to acquire a 2D image. The acquisition of roughly 60 images was followed by computer software processing, initially using a polar coordinate approach to meld the images into a 3D image. The computer software used significant interpolation between images. The result was frequent "stitch" artifact caused by deficiencies in image line-up from patient movement, transducer movement outside the prespecified position, respiratory or cardiac gating artifact, or all of these factors. Although innovative and potentially very powerful for this era, clear limitations remained. Hence, clinical applicability was very limited.[13]

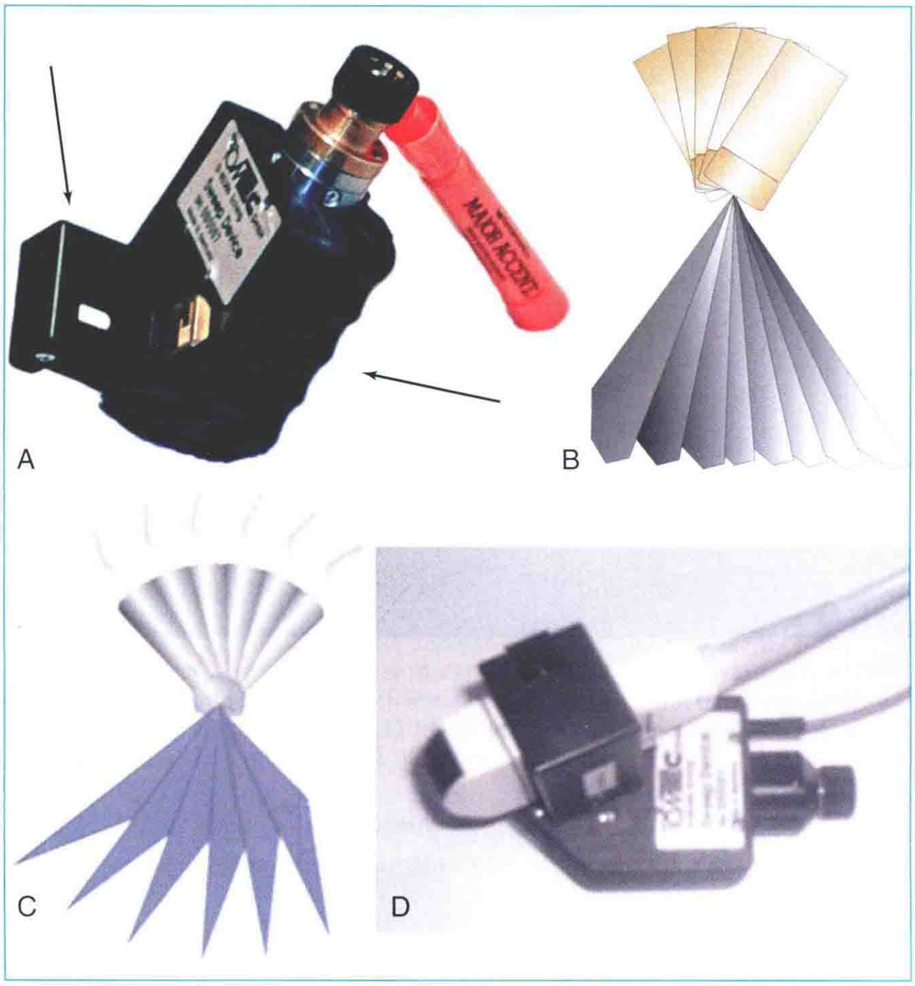

Figure 1-4 **A,** A fanlike device for three-dimensional acquisition. This device, made by TomTec, Inc., stepped the transducer through a fanlike motion. The transducer was held by the square apparatus (*arrows*), and the user held the device in a manner similar to a pistol grip. **B,** The stepwise approach to fanlike scanning. **C,** Ultrasound transducer being held by the fanlike mechanical device in the direction of acquisition. **D,** Mechanical fan device and transducer within. (**B,** Courtesy TomTec, Inc., Munich, Germany.)

Linear or Parallel Scanning

In linear scanning, the transducer was sequentially stepped along a line and obtained images every few millimeters, as opposed to degrees with the rotational and fanlike scans (**Figures 1-6** to **1-9**). Examples of linear scanning using an intravascular ultrasound, predominantly for coronary imaging, as well as a transthoracic echocardiography (TTE) device are shown in the figures. A device, known as "lobster tail," for linear pullback using transesophageal echocardiography (TEE) was available as well. In similar fashion as the previously described linear devices, the lobster tail operated by stepwise pullback of the TEE probe in the esophagus, with imaging at each stop. This TEE probe, developed by TomTec, Inc. (Munich, Germany), included both the TEE probe and the "stepper," that is, the device that moved the probe sequentially (see Figures 1-8 and 1-9). There were several iterations of this technique, including one that involved placing the TEE probe in a water bath within the esophagus to serve as a "standoff" to improve acoustic effects and sharpen the images (see Figure 1-8). The rotational method of scanning with the lobster tail is summarized in Figure 1-9. Further summaries regarding the various types of scanning, early fetal ultrasound, and early computer hardware are shown in **Figures 1-10** to **1-12**.

Text continued on page 11

Figure 1-5 **A,** A device for rotational scanning with a detachable part for holding different-sized transducers of this era. **B,** The detachable transducer holder is back in place. **C,** A transducer (an older mechanical transducer) is shown held in place. **D,** The rotational device with the attached hardware for connecting to the computer that operated the motor on the rotation stepper. **E,** Another version of the rotation device produced by TomTec, Inc. **F,** Rotational scanner shown in close-up. The *arrow* shows the transducer.

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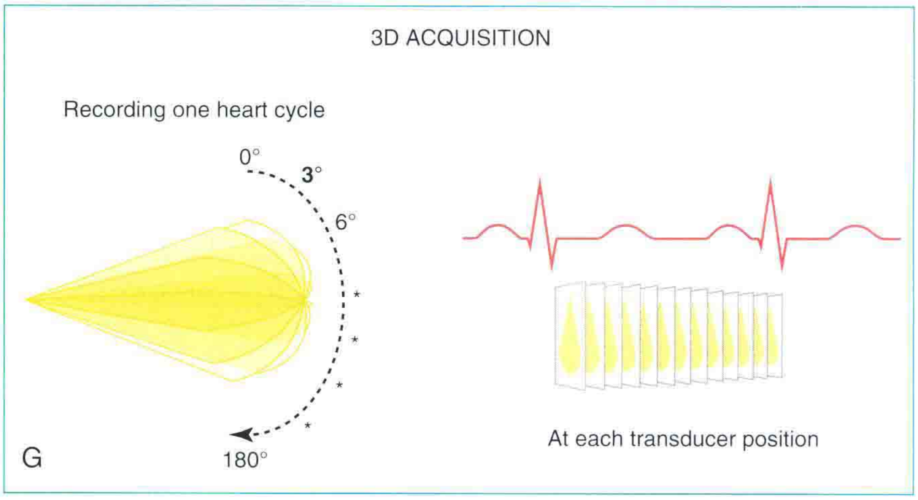

Figure 1-5, cont'd **G,** How rotational scanning was performed with one cardiac cycle obtained every 3 degrees and each cardiac cycle consisting of 15 to 20 frames. (**D** and **G,** Courtesy TomTec, Inc., Munich, Germany.)

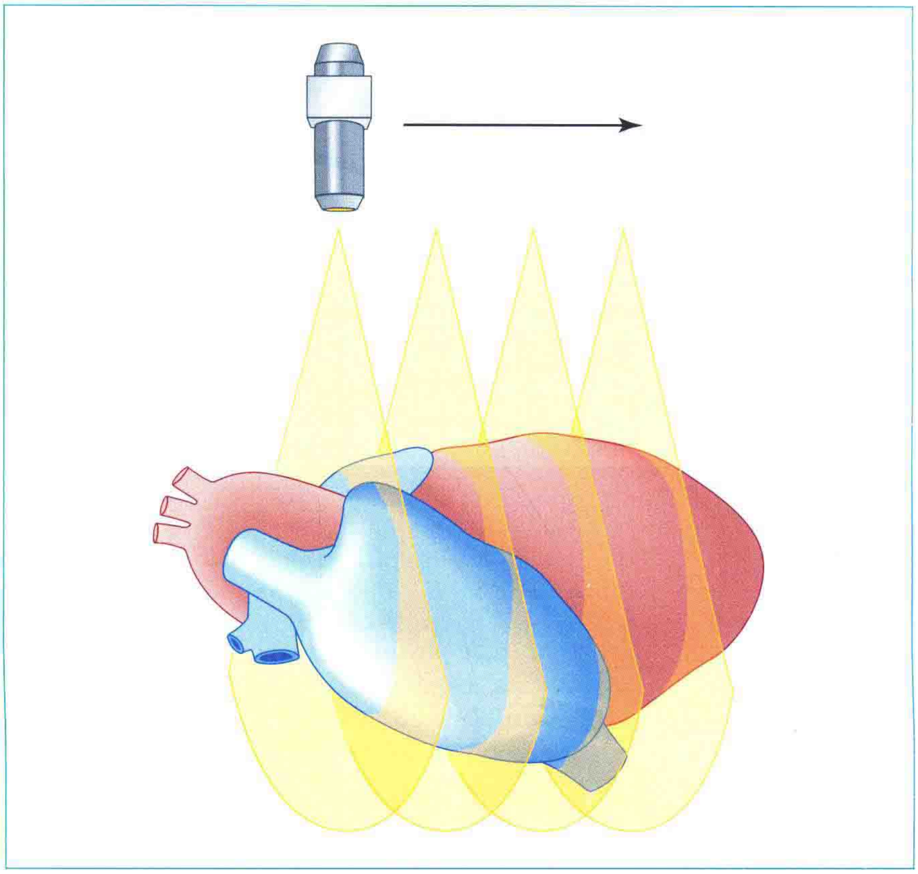

Figure 1-6 Parallel, or linear, scanning. In this schematic, the transducer is sequentially "stepped" through the heart following a linear motion.

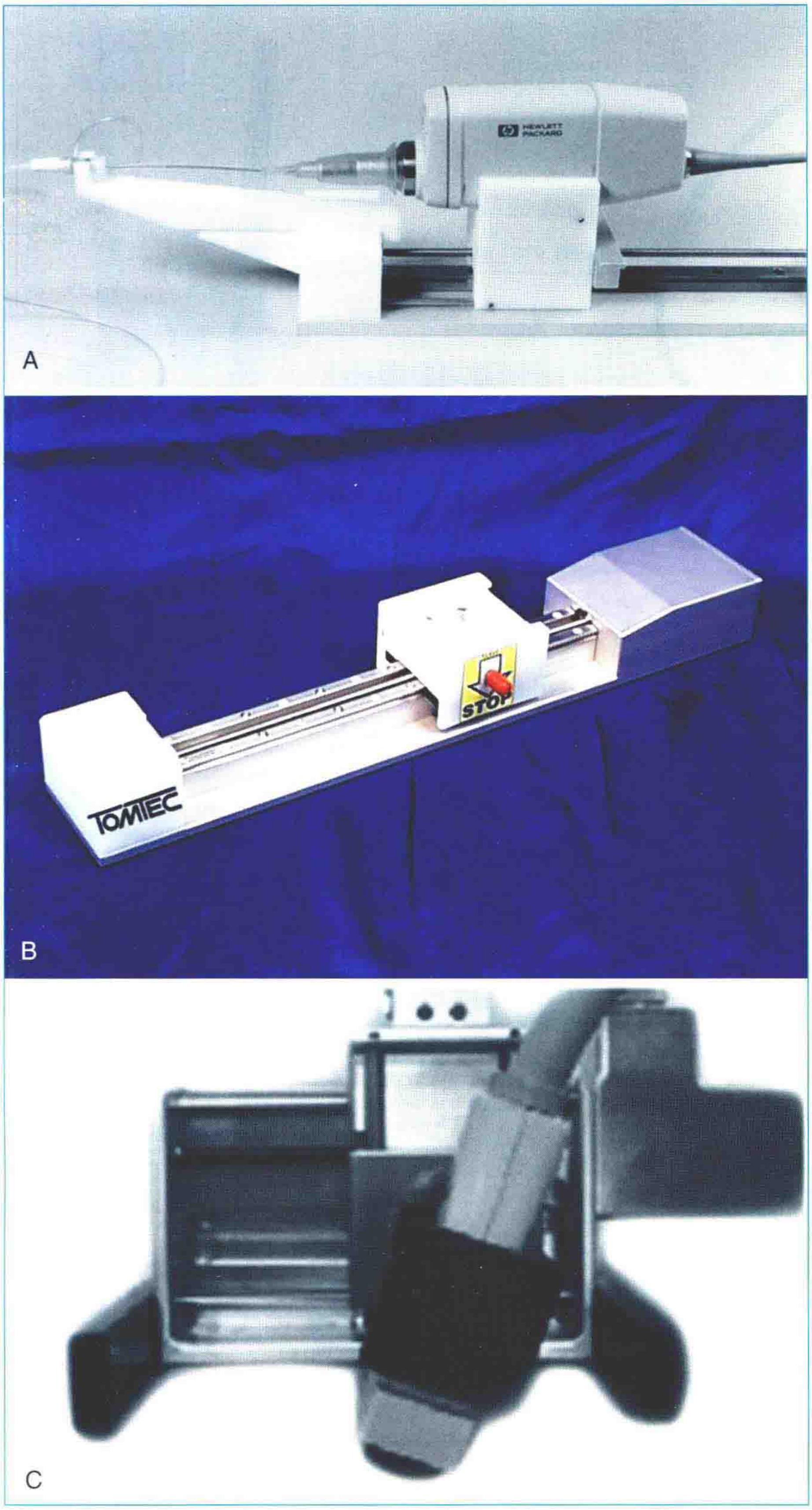

Figure 1-7 Parallel, or linear, scanning. In these iterations of three-dimensional scanning, the transducer was moved in a linear, stepwise fashion. **A** and **B,** The linear stepper device for use with an intravascular ultrasound device. **C,** A linear stepper for a transthoracic transducer. (Courtesy TomTec, Inc., Munich, Germany.)