Percutaneous Interventions for Congenital Heart Disease

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Foreword

This book is the offspring of the annual Frankfurt course of interventional cardiology which has focused strongly on congenital heart disease. This course has, year by year, gained in reputation. It is essentially a practical course. The live case demonstrations are the heart of such meetings. This book reflects the course and is a practical book; a 'how to' book. A quick scan of the 60 or so chapters reveals the galaxy of talent operating and lecturing during the courses and who are now giving their accounts in writing.

As one who was in at the beginning of catheter interventions in congenital heart disease I am filled with wonderment at what is now on offer to the patients. As a young trainee in the late 1960s, Bill Rashkind's introduction of balloon atrial septostomy marked a milestone in the treatment of transposition. Not only did it transform the outlook for babies with this malformation but it marked the start of the quest for practical minimally invasive types of treatment of structural cardiac anomalies. It was admittedly a slow start, with few innovations until the 1980s, but since then the treatment of cardiovascular diseases has been transformed. The advances that have been made have been due, in great part, to the partnership of physicians and industry and it would be hard to overstate the importance of the contribution of our colleagues in industry.

With the rapid incorporation of advanced technologies into this field we have seen procedures and devices come and go. We can expect this dynamic to continue; so this book is a statement of where we stand in 2006 and I am sure that by 2016 a similar book will have many new techniques to offer.

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Foreword

Most knowledgeable interventional historians would argue that the era of lesser-invasive non-surgical cardiovascular therapy began almost 30 years ago when Andreas Gruentzig performed the first successful coronary angioplasty, fulfilling his dream to accomplish catheter-based percutaneous treatment of vascular disease in alert, awake patients. Undoubtedly, Andreas would have delighted in the astounding developments of the ensuing decades, as disciples of his 'simple' procedure applied creativity, technical acumen, and scientific rigor to sculpt the burgeoning interdisciplinary subspecialty of interventional cardiovascular medicine. Importantly, over the years, a typical development pattern has emerged – early stage well characterized procedures involving a restricted lesion subset and patient cohort became generalized to the mainstream patient population after equipment innovations and refinement of physician operator skills. Thus, coronary intervention, beginning with 'plain old balloon angioplasty', begat bare metal stents, atherectomy devices, and drug-eluting stents, finally resulting in a procedure with safe, predictable, and definitive clinical outcomes which could be generalized to most patients with obstructive coronary disease. Soon thereafter, peripheral vascular and neurovascular intervention underwent a similar renaissance, 'borrowing' ideas, technology templates, and operator skills from coronary platforms to extend catheter-based treatments to other regions of the extracardiac vascular system.

The third chapter of this interventional odyssey applies to the current textbook, entitled *Percutaneous Interventions for Congenital Heart Disease*. This newest and most diverse branch of the inteventional tree embraces a potpourri of congenital and acquired cardiovascular disorders, previously left untreated or relegated to surgical therapy alternatives. We have employed the term 'structural heart disease' to encompass a wide variety of non-atherosclerotic and generally non-vascular disease entities, ranging from intracardiac septal defects to valvular lesions. This newcomer on the interventional horizon is unique for several reasons. First, the diversity and complexity of interventional skills required to safely and successfully treat both neonates and octogenarians with advanced cardiac lesions are unprecedented. Second, the intersecting physician groups are far-reaching, spanning pediatric and adult interventional cardiology, imaging specialists (not just angiography, but also echocardiography, MR imaging, and CT angiography), and hybrid surgical therapists. Finally, since many of the cardiac anomalies targeted for catheter-based treatment occur rarely, the focused interventionalists working in this rarified zone have clustered into a small, well bonded fraternity. The purpose of this textbook is to highlight the practical teaching experiences of this congenital and structural interventional fraternity.

For almost a decade, an international live case demonstration workshop has convened in Frankfurt, Germany for the purpose of observing and discussing interventional procedures in this eclectic subspecialty. Directed by Dr Horst Sievert (and more recently with Drs Neil Wilson and Shakeel Qureshi as co-directors), this clinical symposium has become the definitive 'how to' educational event for practicing congenital and structural interventionalists. The current textbook serves as a comprehensive syllabus including a virtual 'who's who' author list, representing the thought leaders from all allied fields under the umbrella of congenital and structural heart disease. The organizational structure is both authoritative and intuitive with easy to navigate sections beginning with the catheterization laboratory environment, new imaging modalities for diagnosis and procedural guidance, and fetal and infant interventions, and marching through an orderly progression of every conceivable congenital and structural lesion category which has been managed using existing or proposed interventional therapies. As with the clinical symposium, this textbook has a familiar stylistic consistency emphasizing clinical treatment indications and practical operator technique issues with helpful procedural 'tips and tricks' and careful descriptions of potential complications. The breadth of this textbook is impressive, extending from commonly recognized conditions to less well established domains, such as exciting new transcatheter valve therapies and intraoperative hybrid VSD closure and stent implantation.

Lest one think that this textbook is merely a compendium of obscure interventional oddities, the subspecialty exploding from the predicate symposium and this textbook represents the greatest potential growth area in all of interventional cardiovascular medicine. Just imagine the consequences if adult transcatheter valve therapy becomes commonplace in patients with aortic stenosis and mitral regurgitation, or if patent foramen ovale closure becomes a

treatment option in patients with refractory migraines, or if left atrial appendage closure becomes an important alternative for patients with atrial fibrillation. In 5–10 years it is entirely conceivable that this small fraternity of interventionalists focused on congenital and structural therapies will multiply into an army of catheter-based therapists with specialized operator skills, an advanced appreciation of cardiac imaging modalities, and a thorough clinical understanding of multi-varied cardiac disease states. This first edition of *Percutaneous Interventions for Congenital Heart Disease* fills a medical literature void and should be heartily embraced by all cardiovascular healthcare professionals, from the curious to the diehard interventional practitioner. I expect as this field continues to transform in the future that subsequent editions of this textbook will help to define the unpredictable progress of this unique subspecialty.

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Preface

This book is intended as a practical guide to the interventional treatment of congenital and structural heart disease for invasive cardiologists in the pediatric and adult fields. Where possible we have tried to emphasize practical aspects of the procedures including the important issues of indications and patient selection, potential pitfalls, and complications. Greater understanding, technical know-how, and wider availability of catheters, balloons, delivery systems, and devices have spread intervention into the realm of acquired valve disease, degenerative disease of the aorta, paravalve leakage, post-infarction ventricular septal defects, and closure of the left atrial appendage. Some of the procedures covered in the book are emerging techniques representing the forefront of interventional treatment today, and will not be practiced in every catheter laboratory.

We have collated contributions from a team of expert interventionists throughout the world in an effort to draw together, via the common link of catheter technology, an approach to congenital and structural heart disease which results in a new emerging specialist, the cardiovascular interventionist.

This book, by complementing practical experience, will be valuable as a practical procedural reference guide to catheter lab staff of all levels and disciplines.

HS, SAQ, NW, ZMH

Section I

1

The ideal cardiac catheterization laboratory: not just for cardiologists anymore – it is hybrid time!

John P Cheatham

Introduction

What would Werner Forsmann say about what has happened since that fateful day, so long ago, when he performed the first cardiac catheterization on himself? Of course, he never actually reached his heart with the catheter the first time *and* he was banished from his promising career as a young surgeon. However, his spirit exemplifies what has now become the modern day interventional cardiologist. Since there is a distinction between the cardiologist trained to treat adults with predominant coronary artery and acquired cardiac disease and those cardiologists specially trained to manage congenital heart disease, the same can be said for the cardiac catheterization laboratories in which these patients are treated. For the purpose of this chapter, the design, equipment required, necessary inventory, and personnel requirements for the modern day lab dedicated to advanced transcatheter therapy for the smallest newborn to the largest adult with complex congenital heart disease will be discussed. The author readily acknowledges the biases instilled in him by his mentor and idol, Charles E (Chuck) Mullins, MD, who has taught many of the congenital heart interventionalists across the globe (Figure 1.1a and b).

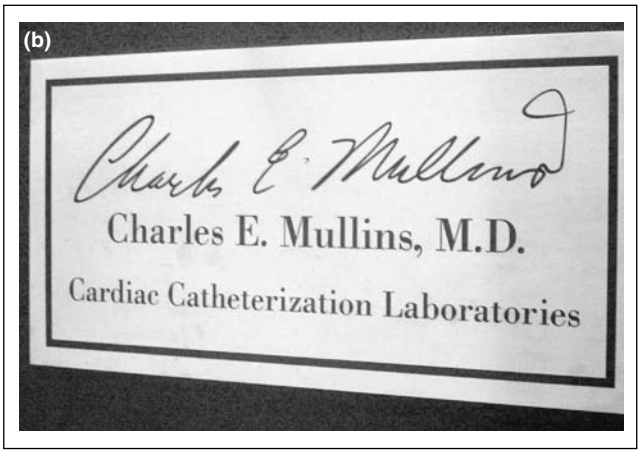

Figure 1.1
Charles E. (Chuck) Mullins MD has taught and inspired many interventionalists specializing in congenital heart disease all over the world. (a) During the dedication ceremony at Texas Children's Hospital, Dr Mullins gathers with some of his 'aging' pupils and his long time cath lab assistant. (b) The new cath labs were named in Chuck's honor – an honor well deserved.

A new era

Historically, cardiothoracic surgeons and interventional cardiologists have had a somewhat competitive relationship. This is especially true with physicians treating coronary and acquired cardiac disease in adults. However, a 'team concept' has always been important when establishing a center of excellence for the treatment of complex congenital heart disease. The collaborative spirit between the cardiac surgeon and the entire cardiology team has advanced therapies offered to patients. More recently, the unique relationship

Figure 1.2
The unique and collegial relationship between the interventional cardiologist and cardiothoracic surgeon has fostered new hybrid treatment strategies for complex congenital heart disease. However, sometimes the members of the team get confused and want each other's job!

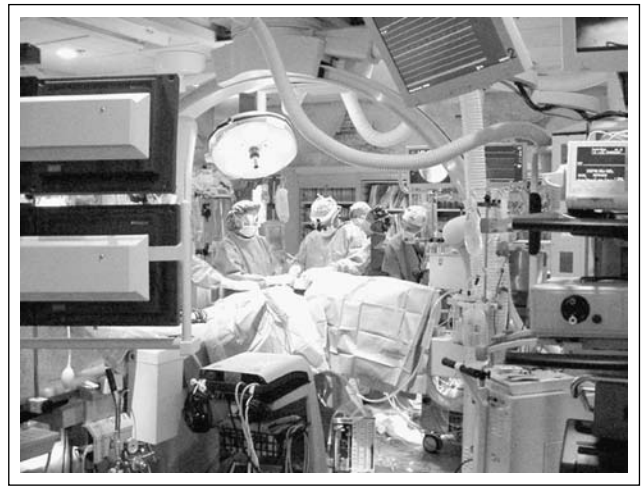

Figure 1.3
During a hybrid cardiac procedure involving the surgical and interventional teams, as well as the perfusionist for cardiopulmonary bypass, the hybrid suite gets crowded very quickly. Space and proper ergonomics in design will overcome many obstacles in a traditional cath lab or operative suite.

between the interventionalist and surgeon has fostered combined transcatheter and surgical therapeutic options – so called 'hybrid' treatment (Figure 1.2).[1–3] This innovative spirit mandates a fresh and open mind to create the 'ideal' venue, or hybrid suite, to expand the capabilities of the traditional cath lab and operating room.[4]

Hybrid suite design

In planning an ideal hybrid suite, there are five major considerations: (1) personnel that will be participating in the procedure, (2) adequate space for the equipment and personnel, (3) equipment that is necessary, (4) informational management and video display, and (5) necessary inventory and consideration of costs.

Personnel

Traditionally, the team responsible to perform both diagnostic and interventional cardiac catheterizations in children and adults with congenital heart disease consists of the interventional cardiologist, an assisting fellow or cath lab nurse, and technicians and nurses who are responsible to monitor the physiologic recorder, the X-ray imaging equipment, and to 'circulate' in the room to assist with the procedure. These team members are former ICU nurses, radiologic technicians, respiratory therapists, and paramedics who receive 'on-the-job training'. Specially trained registered cardiovascular invasive specialists (RCISs) are quite valuable in today's lab, as they are trained in all aspects of cath lab procedures and frequently have adult interventional experience. They are particularly helpful in treating adults with CHD and in the use of coronary stents, vascular closure devices, and small diameter guidewires. All staff are 'cross trained' to be able to run the imaging and hemodynamic equipment and rotate into any job necessary during the procedure. However, as the complexity of transcatheter procedures has evolved, many changes have been necessary to ensure safety and success.[5] A highly trained and competent assistant to the primary operator is imperative. A general pediatric cardiology fellow is usually inadequate to serve in this role today with the higher risk and complicated interventional procedures now performed. Therefore, it is becoming more common to have an advanced level interventional cardiology fellow in the lab. However, many institutions do not have a general or advanced level cardiology fellowship program, therefore, the role of a specially trained interventional nurse practitioner has evolved and offers many advantages.

In addition to the team members mentioned above, dedicated cardiac anesthesia and cardiac ultrasound imaging is mandatory. This requires a staff anesthesiologist with assisting trainee or nurse anesthetist. A staff echocardiographer is also in attendance along with a fellow or technician. One gets the sense that the room is rapidly becoming crowded. By the way, dedicated anesthesia and echo equipment must find a home as well. With the new hybrid procedures, the cardiothoracic surgeon and team will be present which may include an assisting surgeon or resident, a scrub nurse, as well as the perfusionists and accompanying cardiopulmonary bypass machine (Figure 1.3). Now the suite really is shrinking! The electrophysiologist and equipment when electrical therapy or a pacemaker is required can add

Figure 1.4
The appropriate space, design, and equipment are shown here in one of the hybrid suites at Columbus Children's Hospital. Note the flat screen monitors, ceiling mounted equipment, and video and equipment booms to allow easy access to the patient and informational imaging for all personnel.

up to 18 people, all with their specialized equipment, during a single hybrid cardiac catheterization intervention for CHD! So, we have to design the suite to accommodate all of the personnel and the equipment.

Design: space and ergonomics

The space required for a modern day hybrid cardiac catheterization suite is significantly more than a single plane, adult coronary cath lab, or for that matter, the traditional biplane CHD cath lab built 10–20 years ago.[6–9] The suite design must account for the actual working space or procedure room, the control room, a computer 'cold' room, an adjacent inventory supply room, and a new space very important to the modern suite – the induction room, where all of the 'team' can assess the patient and discuss the procedure, as well as administer sedative/anesthetic agents. With dedicated personnel now being assigned to the suites, it is desirable to also plan for administrative office space, personnel offices and workspace, a conference and editing room, a 'break' area, and dressing rooms with bathroom and shower facilities. For the purpose of this chapter, we will confine our remarks to the essential space dedicated to the actual procedure being performed.

Ideally, the hybrid suite should be a minimum of 800 square feet, and preferably 900 square feet (Figure 1.4). A square room, rather than the conventional rectangular suite, allows equal space around the catheterization table for complete patient accessibility – 30′ × 30′ would be 'ideal'. This is especially important when interventional procedures may be performed from either femoral, jugular, or subclavian sites, and let's also not forget about transhepatic access. In the majority of hybrid procedures, access is

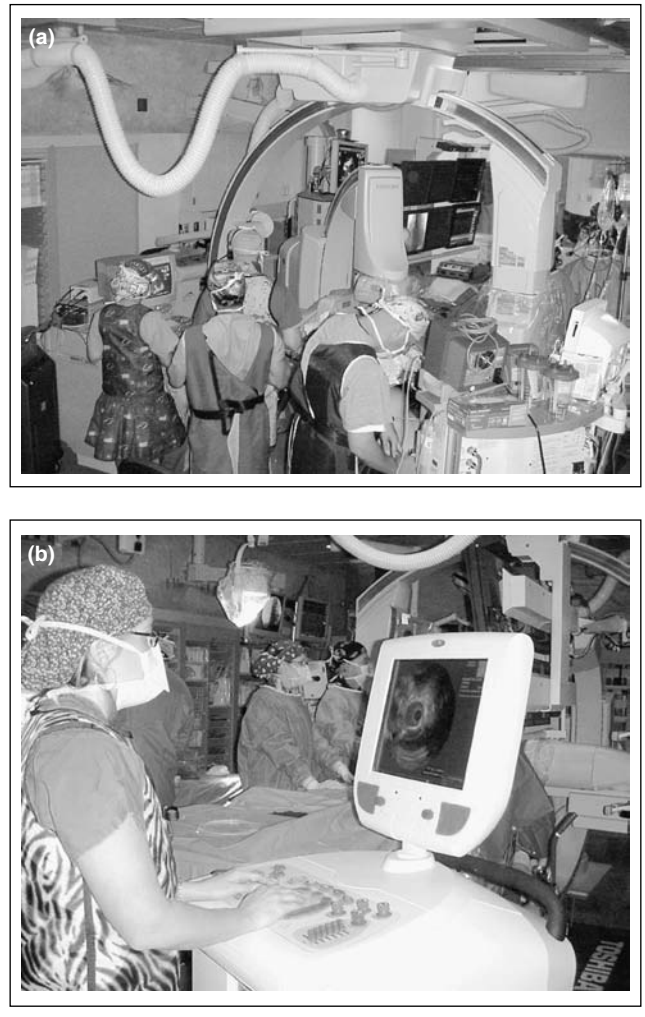

Figure 1.5
It is important to design appropriate space for the echo and anesthesia teams to be involved in transcatheter or hybrid therapy for congenital heart disease. (a) The echo and anesthesia teams have a completely free space at the head of table during TEE guidance of device closure. (b) In addition, during IVUS or ICE examination, the space at the foot of the table must also allow the team to do their job.

required through a median sternotomy and personnel will be on both sides of the table. There must be room for the anesthesiology team and anesthesia equipment at the head of the patient and to either side, while space must also be available for the echocardiography personnel and echo machine at the head of the patient during transesophageal echo (TEE), and at the end of the table for intracardiac echo (ICE) or intravascular ultrasound (IVUS) (Figure 1.5a,b). The perfusionist and cardiopulmonary bypass machine will usually be positioned on the side opposite the surgeon and/or interventionalist, making the width of the room extremely important and different from a traditional cath lab – hence, a square room.

Figure 1.6
The control room should be designed to allow personnel to view the catheterization procedure without obstruction. Note the clear line of view down the table during the final phase of hybrid suite construction.

Figure 1.7
A relatively new concept is the use of an 'induction room', which allows access to the patient and family by all team members in a quiet environment. Wall mounted anesthesia equipment conserves space and allows sedation or induction of anesthesia as needed. The room should be directly connected to the hybrid suite, as shown here.

The control room should be as wide as the hybrid suite (25–30 feet) and approximately 10 feet in depth. This will allow all of the personnel, along with the physiologic and digital X-ray imaging equipment and monitors, to be strategically placed. In addition, the digital review station and archiving system should be located in this room. In the combined interventional/electrophysiology suite, appropriate electrophysiology (EP) recording, pacing, radiofrequency ablation, and three-dimensional (3D) mapping equipment must also be placed in the control room. This room should be designed in order for the personnel to view the procedure directly by looking down the table from the foot to the head of the patient (Figure 1.6). This ensures an unobstructed view of the procedure, regardless of the position of the biplane equipment or the team. Therefore, the patient table should be parallel to the viewing angle of the control room. The adjacent computer or 'cold room' size will be dependent on the manufacturer's specifications, but should allow easy access for maintenance or repair work to be performed. When building multiple suites, this room can be shared to conserve space.

The suite should also have an adjacent and ample supply room to store the extra inventory and consumable equipment that is not located in the cabinet storage within the procedure room. A blanket warmer is placed here, as well as other non-consumable equipment. If possible, the adjacent supply room should be approximately 100–120 square feet and should be directly accessible from the procedure room for maximum efficiency. If there are multiple suites, then a larger central supply room could be used that is accessible to both suites.

A relatively new concept in both surgery and interventional cardiology is the use of an 'induction room' adjacent to the hybrid suite (Figure 1.7). This room becomes very important since it allows the interventional, anesthesia, and surgical teams direct access to the patient and family, while maintaining a quiet and comforting environment to explain the procedures, perform history and physical examination, and to administer sedation. By installing small, space efficient, anesthesia machines that can be mounted on the wall, induction can be performed here as needed. In addition, this room may serve as a separate TEE room while an interventional catheterization is being performed, allowing maximum efficiency of the anesthesiology team. Ideally, this room should be approximately 12 feet by 17 feet, which will allow the appropriate family members and personnel to interact in a comfortable environment.

Not mentioned is the mandatory soil or 'dirty' room, where reusable equipment is washed, and which must be separate from the 'clean' scrub room, as per occupational safety and health administration (OSHA) standards. Also, when building two hybrid suites, it becomes apparent that a centrally located scrub area with two separate sinks be located immediately outside the procedure rooms with open access from both control rooms, but with appropriate barriers for infection control. This allows maximum efficiency and entry into both suites, while maintaining safety and a sterile environment.

Equipment

What used to be a pretty simple list of equipment needs 10 years ago has mushroomed into a huge cloud of needs,

wants, and money! Biplane X-ray imaging equipment and a physiologic monitoring system with recording and reporting capabilities occupied most of the capital expense requirements of the traditional lab 10 years ago. However, the new hybrid suite's capital equipment list has grown proportionally, incorporating many services within a Heart Center.

Beginning with X-ray equipment, we certainly live in a new age of imaging. While some might argue the merits of biplane versus single plane fluoroscopic and angiographic units, no one would dispute the clear advantages of displaying complex spatial anatomy using biplane cameras. This is especially true when performing transcatheter procedures in the tiniest preterm neonate to the 200 kg adult with complex CHD. So in a perfect world and without consideration of costs or space requirements, a modern biplane, digital cath lab is mandatory to achieve optimal imaging for the complicated interventional procedures of today.

Today, no one would argue the merits of digital (film free) radiographic systems. However, for some interventionalists over the past 10 years, it was a slow process to 'give up' cine film, X-ray processing rooms, and splicing lessons for fellows. The obvious advantages of digital technology are real time access and viewing, no deterioration of angios, ease of storing, managing, and retrieving image data, and labor savings for the procedure. The digital images are easily accessible both inside and outside the hospital using a web server, as well as by remote satellite transmission. Yet, just as the 'digital age' in cardiac catheterization began over a decade ago, we now live in the world of PC-based digital platforms and flat panel detectors (FPDs). This began with General Electric Medical's introduction of a single plane FPD approximately 5 years ago, then the PC-based digital platform for hemodynamic monitoring systems arrived in 2004, and culminated with the introduction of biplane FPD technology in 2005 by Siemens Medical and Toshiba Medical Systems Corporation. The targeted specialties for this new equipment are centers specializing in CHD cardiac catheterizations, advanced electrophysiology laboratories, and neuroradiology treatment centers.

We must ask, what are the advantages of FPD technology?[10,11] The definition of FPD is a compressed or flat detector which uses semiconductors or thin-film transistors (TFTs), converts X-ray energy into electrical signals, and creates X-ray images. Currently, indirect conversion FPD technology is used for biplane systems. Eventually, direct conversion technology may be used, once the 'blanking' and frame rate limitations are overcome in the biplane configuration. Direct conversion will improve resolution as the image is never converted to light. The FPD will likely replace all existing X-ray detectors, such as image intensifier (II)-TV cameras and spot film cameras, as well as film screen systems. For cardiovascular work, the small profile of the detector size will allow a more compact design and facilitate improved patient access. In addition, high image quality with improved blood vessel detectability by high modulation transfer function (MTF) and no distortion will be an advantage. Finally, 3D digital tomography and interventions may be possible. If there has been a downside to this technology, it has been the lack of appropriate Windows™ software programs being provided by all manufacturers during this introductory phase. This should improve with time, as more software programming specialists are incorporated into the research and development teams of manufacturers.

In the dedicated CHD hybrid suite, patient accessibility is equally important to high quality imaging. Therefore, since the 3D gantry positioner was introduced by General Electric Medical over a decade ago, other companies have now realized the importance of patient access in a biplane lab. Since a 3D gantry allows rotation of the C-arm in the x, y, and z axes, this allows additional space at the head of the table to accommodate the anesthesia and interventional teams. However, with the original design by General Electric and later Siemens Medical, the space was still crowded. The most recent and innovative design has come from Toshiba Medical Systems Corporation with a 5 axis C-arm positioner with biplane FPD (Infinix CF-i/BP), which allows movement in five axes around the patient, with rotation of the C-arm base to −135° or +135°, which actually places the C-arm on the 'foot' side of the lateral camera (Figure 1.8). This allows a completely 'head free zone' of 180° while in a biplane configuration, allowing easy access to the patient by the anesthesia, echo, and interventional teams (Figure 1.9). It is also highly beneficial to the electrophysiology service during complex studies with transvenous pacemaker implantation.

All teams must have not only free access to the patient, but also a clear line of site to the image display monitors. Speaking of monitors, the days of the CRT monitors are coming to an end. Flat screen monitors are achieving comparable black-white and line resolution, and are ergonomically more versatile in a biplane laboratory. They take up less space, are lighter, and can be mounted on a 6 monitor gantry that can be strategically placed around the procedure table to allow optimal viewing by all personnel participating in the procedure, regardless of location (Figure 1.10). This gantry should be able to be placed on either side of the table, as well as over the table at the head or foot of the patient. In the hybrid suite, it is also important to install a surgical light mounted strategically on the ceiling. We also prefer to mount all other accessory equipment from the ceiling, i.e., contrast injector with wall mounted controls, local spotlight, and radiation shield.

The other components of X-ray imaging equipment found in the hybrid suite are fairly standard by today's standards. TV cameras using the charged coupled device (CCD) technology, developed by Toshiba Medical Systems Corporation, to improve brightness and resolution; X-ray tubes using spiral-grooved and liquid metal bearing technology, introduced by Phillips Medical, Inc to eliminate noise and reduce the delay in fluoro/digital acquisition; and

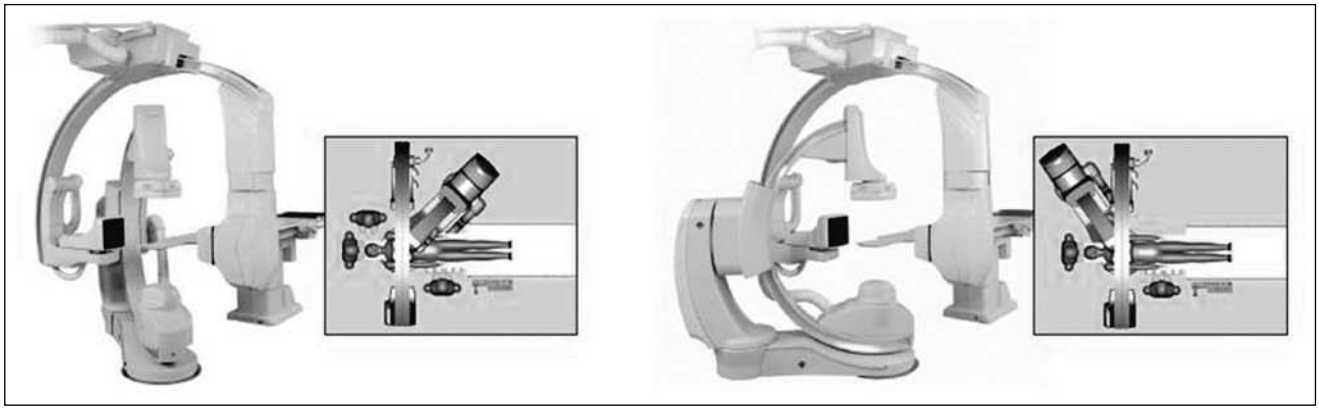

Figure 1.8
The new design of the Toshiba Infinix CF-i/BP positioners allows rotation of the C-arm base from −135° to +135°. This schematic drawing demonstrates the 180° of 'head free zone' afforded by this new design.

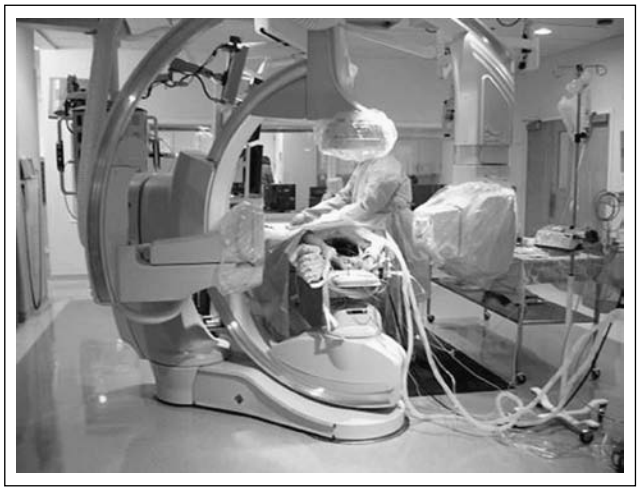

Figure 1.9
During a cardiac catheterization procedure, the open space at the head of the table is nicely demonstrated here. There is plenty of room for the interventional, echo, and anesthesia teams to perform their jobs.

Figure 1.10
Flat screen monitors have now approximated CRT monitors in terms of resolution. The lighter, more compact configuration of the flat screen monitors allows a gantry holding six monitors to be easily positioned at any location for the hybrid team to view the images, as depicted here during a stage I hybrid palliation for hypoplastic left heart syndrome (HLHS).

high frequency generators are now uniformly offered by all manufacturers. Furthermore, while using different technology, radiation dose management is a priority with all manufacturers to protect the patient and all of those participating in the longer interventional catheterization procedures being performed today.[12]

An important, but forgotten, component of the new hybrid suite is the procedure table. Traditional cath lab tables have certain features that are well suited for X-ray imaging, patient positioning, and quick and easy 'free float' movement, and that are electronically integrated into the manufacturer's X-ray imaging equipment. In addition, some tables have the ability to be placed in the Trendelenburg position. In comparison, the traditional operating room table is narrower, shorter, less 'fluoro friendly', and does not provide 'free float' capabilities. Additionally, the table has the very important feature of 20–30° lateral tilt which provides the cardiothoracic surgeon with exposure to the desired operative field ergonomically, while the Trendelenburg position is also possible. So, currently, either the surgeon or the interventionalist must make sacrifices while performing hybrid procedures in the traditional operative or catheterization suite. A new hybrid table is essential to facilitate new hybrid management strategies for complex CHD. The table must be manufactured by the X-ray equipment companies in order to provide 'connectivity' to the imaging equipment and possess tableside controls. This table must possess all of the above mentioned specifications, so will require input

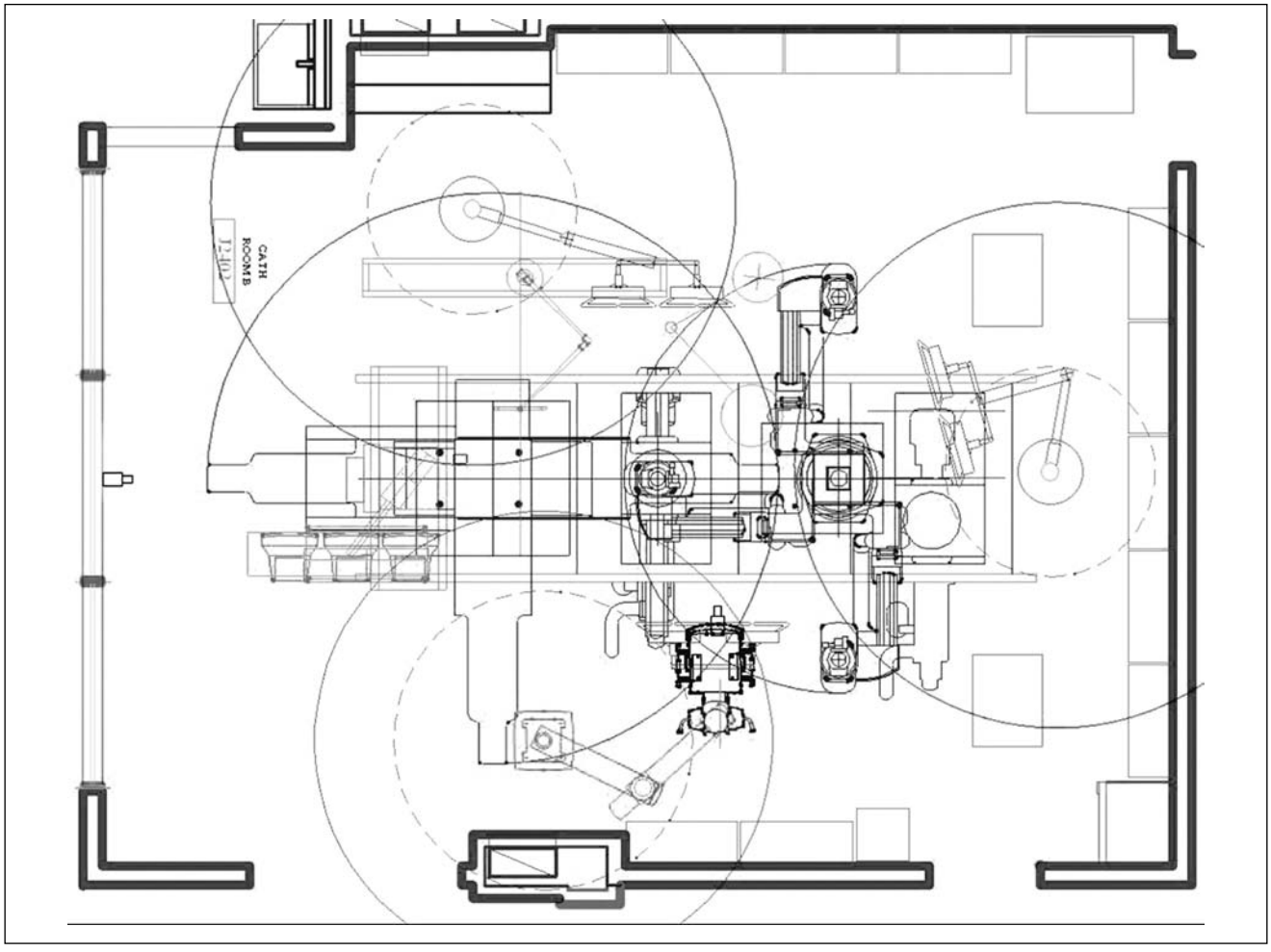

Figure 1.11
The schematic drawing of our hybrid suite demonstrates the importance of careful planning, input from multiple members of the Heart Center, and collaboration with several industry representatives. Note the video monitor and equipment boom design to ensure all personnel can view the appropriate images during the procedure, regardless of their location in the suite.

from both cardiothoracic surgeons and interventional cardiologists as they are being designed. Such a hybrid table is being planned by both Toshiba Medical Systems Corporation and Siemens Medical. Stay tuned!

Informational management, video display, and transport

Staggering amounts of information are generated in today's healthcare environment and these data need to be readily available during the procedures. In our Heart Center, we attempted to provide access for angiography, echocardiography (including TTE, TEE, ICE, and IVUS), and the PACS system (CT, MRI, and chest X-ray) from any computer inside or outside the hospital with a dedicated web server and VPN access. This same information must be readily available in the new hybrid suites where complex procedures and decision-making are being performed by the multidisciplinary team. The information needs to be accessible to all participants in the suite and must be specific to their assigned tasks. If the staff moves around the room, so must the displayed images. Furthermore, all of this information should be able to be transmitted to other sites within the hospital, i.e. operative room, teleconference center, or research lab, as well as to sites anywhere in the world, i.e. educational conferences, outside referring physicians for patient care, and teaching workshops. A dedicated and expansive archiving system is imperative for the digital technology of today. The data must be sent 'seamless' from the archived source to the active procedure and/or educational site.

In an ideal world, money, space, and hospital administrative support would be unlimited. So, let's begin with the video display within the hybrid suite. Flat screen monitors are strategically placed around the room, mounted to ceiling booms with a rotational axis that provides viewing from any location (Figure 1.11). We chose to enlist the expertise of

Figure 1.12
A large video router and informational management unit is located in our teleconference center and provides interconnectivity to the hybrid suites through the smaller video router and cameras within each suite. In turn, the operative suite and research laboratory can also be connected through the teleconference center, providing a 'video network topology' for worldwide education and patient care.

Stryker Communications to fulfill these needs. Two monitors are mounted on three video booms, while one of the booms also serves as an equipment boom. Mounted on the equipment boom is a defibrillator, fiber optic surgeon's headlight, electrocautery, and a pan/tilt/zoom video camera. A second camera is mounted on the wall above the control room, providing expansive views of the suite and the procedures being performed. A video router is located within each suite and allows any image to be displayed on any video monitor, giving each staff member optimal viewing of the information pertinent to their job. In turn, the video router in the hybrid suite is connected to a larger management and routing unit within the teleconference center, serving as the 'mother ship' (Figure 1.12). All information can be transmitted anywhere in the world from this location. We believe this 'video network topology' to be the framework of the future.

Inventory

Every cardiac catheterization procedure in patients with CHD requires a large inventory of 'routine' consumable items. In addition, each interventional procedure requires an additional inventory of special and very expensive consumable materials. Words from my mentor, Dr Mullins, are etched in my mind. 'In a congenital heart laboratory, all consumable items must be available in a very wide range of sizes in order to accommodate every patient's size, from the tiniest premature neonate to the largest adult patient. A cardiac catheterization procedure *never* should be compromised or terminated because of the lack of a necessary piece of consumable equipment.' However, these special consumables will vary with the individual operator's experience and credentials, as well as with the availability of a particular device or material in any particular part of the world. Equally important in determining the inventory is the individual hospital administrator's 'budget' control. We are very fortunate with tremendous hospital support, which seemingly allows unlimited access to all available consumables, i.e. balloon catheters, devices, delivery systems, stents, guidewires, RF perforating systems, all imaging equipment (TTE, TEE, ICE, IVUS), etc. – which are justified and 'reasonable'. Accordingly, our inventory consumable costs are over $1 million, so it is incumbent upon the cath lab manager and medical director to maintain strict inventory control and management. New 'bar coders' can be used to scan all consumables used during the procedure to maintain an accurate accounting for billing purposes, as well as maintaining a computerized inventory and order management system. Most new hemodynamic systems have an inventory management program that can be used for this purpose. Unfortunately, economics, rather than necessity, will continue to dictate the practice of medicine.

Summary

In conclusion, collaboration between the interventional cardiologist and cardiothoracic surgeon continues to increase

as the hybrid strategies for complex CHD evolve. Making informational resources available when and where they are needed can have a dramatic impact on patient care. The implementation of a hybrid cardiac catheterization suite is a result of careful planning involving multiple disciplines, including Heart Center medical staff, equipment manufacturers, architects, contractors, and information technology specialists. Specially designed equipment and trained personnel are paramount to success. A huge inventory of consumables is required and must be judiciously managed. However, there is no substitute for a collegial and professional relationship and understanding among the Heart Center staff of the ultimate goals of success. Finally, it must be recognized that a progressive and forward thinking hospital administrative staff is a prerequisite for the planning, building, and financial support necessary for the ideal hybrid cardiac catheterization suite to become a reality.

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Section II

Imaging modalities in the cath lab

2

Angiography

Lee Benson and Haverj Mikailian

Introduction

Accurate anatomic and physiologic diagnosis is the foundation of a successful catheter based therapeutic procedure. As such, a number of complementary imaging modalities have been developed to define, in real time, specific aspects of the heart and circulation for interventional applications. In the evolution of our understanding of the cardiovascular system, angiography with fluoroscopy was the first to be developed, and the angiography suite remains the cornerstone around which the interventional suite is built.

This chapter will include a discussion of standard angiographic approaches and how to achieve them. Emphasis will be placed on the application of these projections as applied to interventional procedures. A detailed description of the physical principles of image formation is beyond the scope of this chapter and the interested reader is referred to other sources for more detailed information.[1]

Angiographic projections

In the therapeutic management of the child with a congenital heart lesion, the spatial orientation and detailed morphology of the heart and great vessels are of critical importance. As the operator enters the laboratory, an overall understanding of the anatomy should have been synthesized, based upon information from other imaging modalities such as chest roentgenography, echocardiography, and computed tomographic and magnetic resonance imaging. As such, the angiographic projections used in the procedure will be 'tailored' to outline the lesion to allow appropriate measurements and guide the intervention.[2]

In most children, the heart is oriented obliquely, with the left ventricular apex being leftward, anterior and inferior, then the heart base (Figure 2.1). The interventricular septum is a complex geometric three-dimensional structure that takes an 'S' curve from apex to base (Figure 2.2), the so-called sigmoid septum. From caudal to cranial the interventricular septum curves through an arc of 100° to 120°. The right ventricle appears as an appliqué to the left. To address this unique topology, today's angiographic equipment allows a wide range of projections, incorporating caudocranial or craniocaudal angulations to outline or profile specific structures. The up-to-date laboratory of today consists of independent biplane imaging chains which, with the proper selection of views, minimizes overlapping and foreshortening of structures.

Terminology

Angiographic projections are designated either according to the position of the recording detector (image intensifier or flat panel detector) or the direction of the X-ray beam toward the recording device. Generally speaking, in cardiology, the convention is the former, and all terminology discussed henceforth will be using that convention. For example, when the detector is directly above a supine patient, the X-ray beam travels from posterior to anterior and the *angiographic projection* is designated postero-anterior (PA), but based upon detector *position* it is called frontal, and the position of the detector is by convention at 0°. Similarly, when the detector is moved through 90°, to a position besides and to the left of the patient, a lateral (LAT) projection results. Between 0° and 90° there are a multitude of projections termed left anterior oblique (LAO), and when the detector is moved to the right of the patient, a right anterior oblique projection (RAO) is achieved. As in the LAO projection, there are numerous RAO projections depending on the final angle from the midline. When the detector is posterior to the patient (the X-ray tube is anterior), then a right (RPO) or left (LPO) posterior oblique projection occurs (Figure 2.3).

Standard detectors mounted on a C-arm or parallelogram not only allow the above positions, but the detectors can be rotated around the transverse axis, toward the feet or head, caudal or cranial (Figure 2.4).

In summary, the conventional terms RAO, LAO, PA, and left-LAT designate the position of the recording detector. The LAT position usually will have the detector to the left of the patient by convention, and will be so implied throughout this chapter. Finally, for clarification, while the

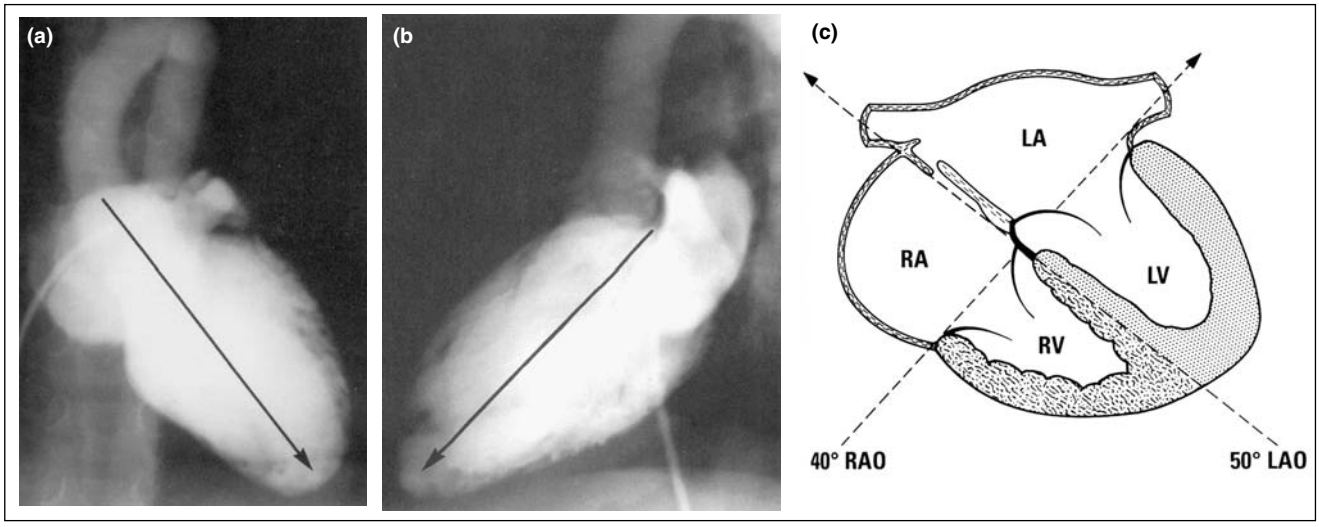

Figure 2.1
The typical lie of the heart in the chest. (a) Frontal and (b) lateral projections of a left ventriculogram demonstrate the axis of the heart. The apex points anteriorly, inferiorly, and leftward. Panel (c) is a diagram of how a standard mid-RAO and a standard mid-LAO profile images of the axes of the heart. The RAO profiles the atrioventricular groove, and presents the ventricular septum *en face*. The mid-LAO view profiles the intraventricular septum, and separates the left and right ventricular and atrial chambers. (Modified from Culham[1] with permission.)

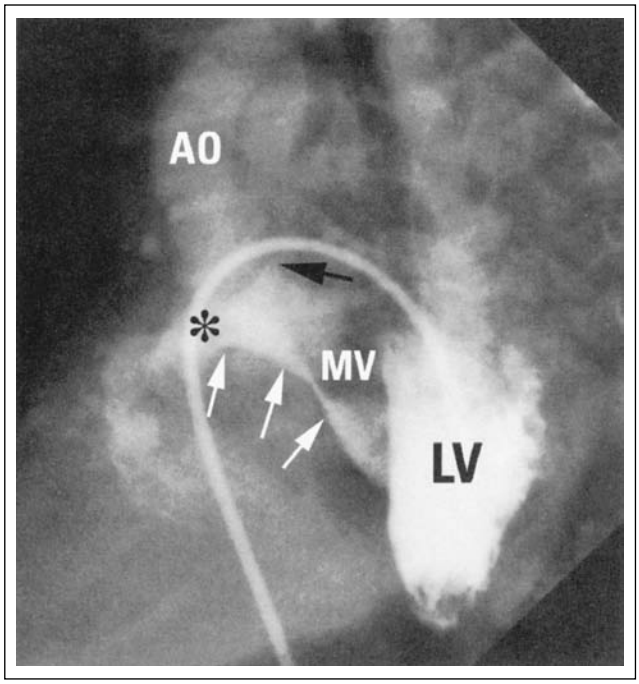

Figure 2.2
The sigmoid septum. A venous catheter is in the apex of the left ventricle through the mitral valve, in the long axis oblique projection. The sigmoid configuration of the septum is well seen (white arrows). Aortic–mitral continuity is noted (black arrow). Contrast is seen mixing across a ventricular defect (asterisk). (Modified from Culham[1] with permission.)

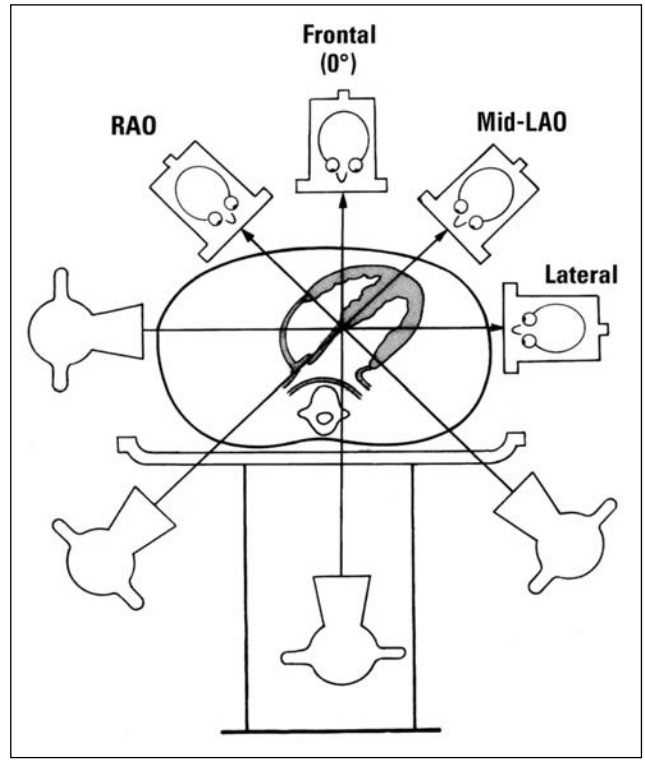

Figure 2.3
Naming the standard projections with the X-ray tube under the table. This diagram illustrates the various positions of the detector/X-ray tube. The patient is supine, and the view is from the patient's feet, looking toward the head. (Modified from Culham[1] with permission.)

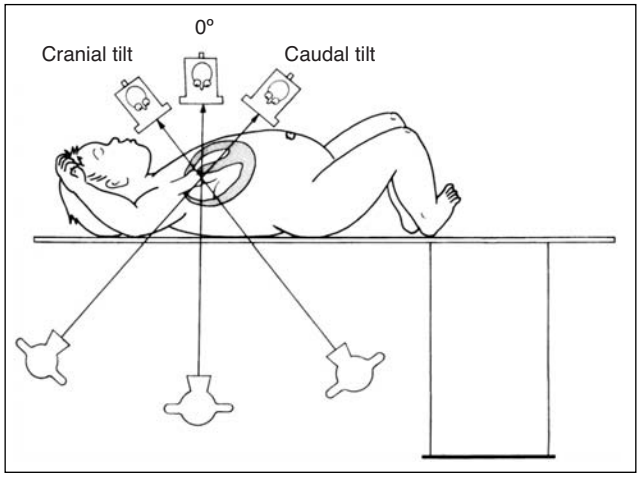

Figure 2.4
Naming the standard projections with the X-ray tube under the table. Cardiologic convention is such that cranial and caudal tilt refers to the detector position. (Modified from Culham[1] with permission.)

term projection refers to the path of the X-ray beam, to be consistent with cardiologic practice, projection or view will refer to the position of the detector.

Biplane angiography

As outlined in an earlier chapter discussing the ideal catheterization suite, dedicated interventional catheterization laboratories addressing congenital heart defects require biplane facilities.[3,4] Biplane angiography has the advantage of limiting contrast exposure and of facilitating the assessment of cardiac structures in real time in two projections simultaneously. However, this is at a cost, as these facilities are expensive, and with existing image intensifiers and newer flat panel detectors, extreme simultaneous angulations can be compromised. The choice of a set of projections will depend upon the information required, equipment capabilities, and the physical constraints to patient access. Standard biplane configurations include RAO/LAO, and frontal or lateral projections, with additional cranial or caudal tilt. The possible combinations are endless (Table 2.1 and Figure 2.5).

Cranial-LAO projections

A clear working understanding of these projections is of critical importance in developing a flexible approach to congenital heart defect angiography, and intervention. The practice of using 'cookbook' projections for each case *may*

Table 2.1 *Summary of projections*

Projection	Angles	
Single plane projections		
Conventional RAO	40° RAO	
Frontal	0°	
Shallow LAO	1° to 30°	
Straight LAO	31° to 60°	
Steep LAO	61° to 89°	
Left lateral	90° left	
Cranially tilted RAO	30° RAO + 30° cranial	
Cranially tilted frontal (Sitting up view)	30° or 45° cranial	
Cranially tilted shallow LAO	25° LAO + 30° cranial	
Cranially tilted mid-LAO (Long axis oblique)	60° LAO + 20° to 30° cranial	
Cranially tilted steep LAO (Hepatoclavicular view)	45° to 70° LAO + 30° cranial	
Caudally tilted frontal	45° caudal	
Biplane combinations	*A plane*	*B plane*
AP and LAT	0°	Left lateral
LXO	30° RAO	*60° LAO + 20° to 30° cranial*
Hepatoclavicular view	*45° LAO + 30° cranial*	120° LAO + 15° cranial
Specific lesions		
RVOT-MPA (sitting up)	*10° LAO + 40° cranial*	Left lateral
Long axial for LPA (biplane)	30° RAO	60° LAO + 30° cranial
LPA long axis (single plane)		60° LAO + 20° cranial
ASD	*30° LAO + 30° cranial*	
PA bifurcation and branches	*30° caudal + 10° RAO*	*20° caudal*

Primary projections are in italics. RAO, right anterior oblique; LAO, left anterior oblique; AP, antero-posterior; LAT, lateral; RVOT, right ventricular outflow tract; MPA, main pulmonary artery; LXO, long axis oblique; LPA, left pulmonary artery; ASD, atria septal defect; PA, pulmonary artery.

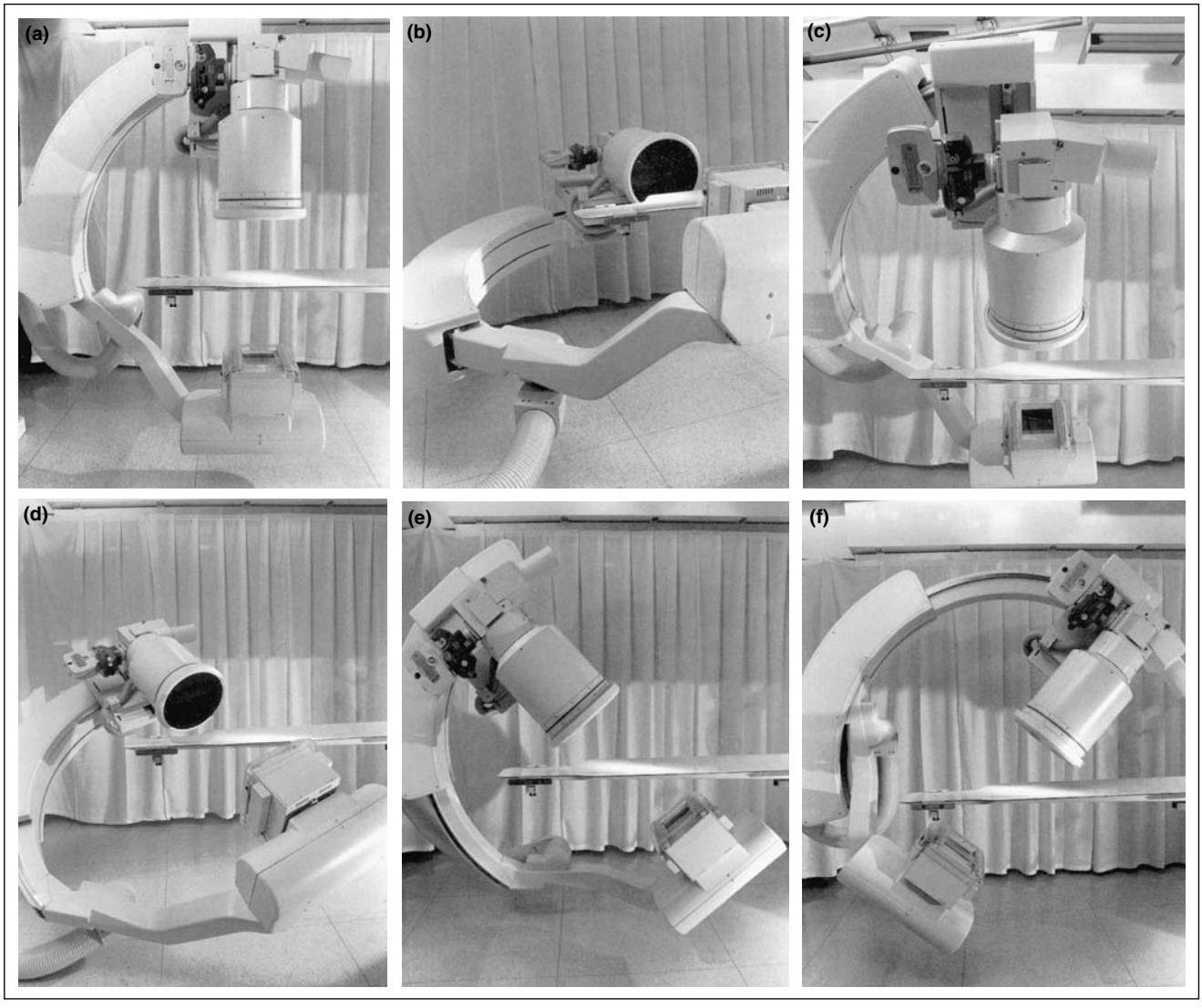

Figure 2.5
Standard projections. (a) Frontal (PA), (b) Lateral (LAT), (c) RAO, and (d) mid-LAO with cranial tilt. (e) Cranially tilted frontal (sitting up); (f) caudally tilted frontal. (Modified from Culham[1] with permission.)

allow acceptable diagnostic studies, but will fall short of the detail required to accomplish an interventional procedure. However, a comprehensive understanding of normal cardiac anatomy, especially the interventricular septum, allows the operator to adjust the projection to optimize profiling the region of interest.

There are a number of 'rules of thumb' that allow the operator to judge the steepness or shallowness of an LAO projection. Of importance is the relationship of the cardiac silhouette to the spine, the ventricular catheter, and the ventricular apex.

To optimize the profile of the mid-point of the *membranous ventricular septum* (and thus the majority of perimembranous defects), two-thirds of the cardiac silhouette should be to the right of the vertebral bodies (Figures 2.6 and 2.7). This will result in a cranially tilted left ventriculogram showing the left ventricular septal wall, the apex (denoted by the ventricular catheter) pointing toward the bottom of the image. A shallower projection will have more of the cardiac silhouette over towards the left of the spine and profile more the infero-basal component of the septum, ideal for *inlet type ventricular defects*. This projection allows for evaluation of atrioventricular valve relationships, inlet extension of perimembranous defects, and posterior muscular defects. A steeper LAO projection can be used to profile the *outlet extension of a perimembranous*

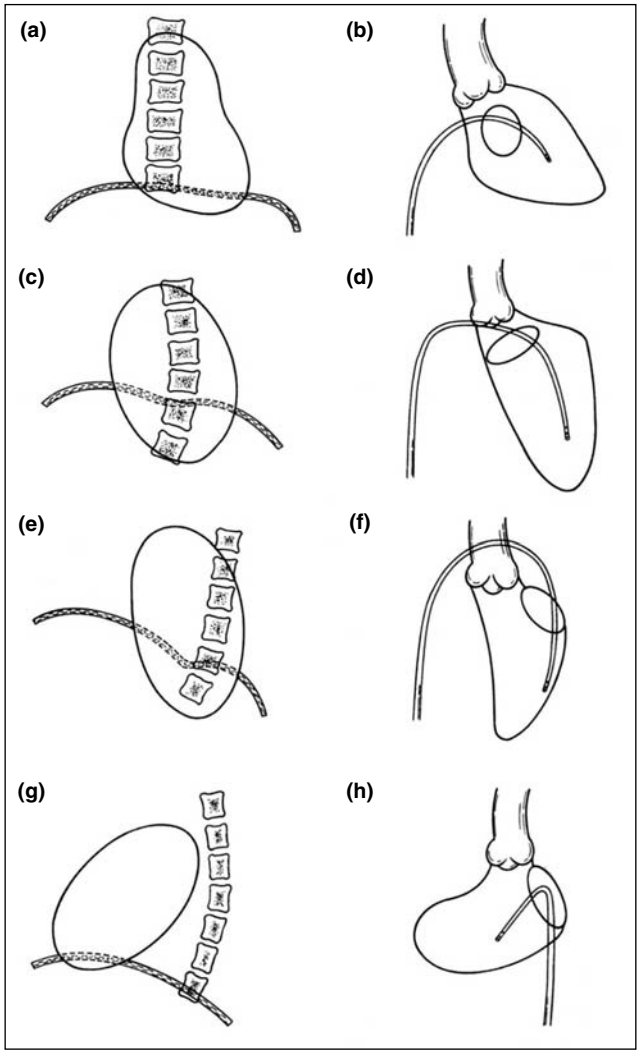

Figure 2.6
Setting up a standard LAO projection. To achieve the LAO projection, attempt to adjust the detector angle such that two-thirds of the cardiac silhouette is to the left of the spine, as in (e). If a catheter is through the mitral valve in the left ventricular apex, it will point to the floor, as in (f). In this view, the intraventricular septal margin points toward the floor. The so-called 4-chamber or hepatoclavicular view is achieved by having half the cardiac silhouette over the spine, as in (c). A catheter across the mitral valve will appear as in (d). A steep LAO projection will have the cardiac silhouette shown in (g), and a transmitral catheter in the left ventricle will appear as in (h). (a) and (b) show the frontal projection. (Modified from Culham[1] with permission.)

defect, and anterior muscular and apical defects. As noted in Figure 2.6, the ventricular catheter in the cardiac apex can be used to help guide the projection, but only if it enters the chamber through the mitral valve. If catheter entry is through the ventricular defect or retrograde, it tends to be more basal and left lateral.

Modification of the cranial LAO projection will have to be made if there is a discrepancy in chamber sizes, and the septum rotated, such that a steeper or shallower projection may be required. Also, it is assumed that the patient is laying flat on the examining table, but if the head is turned to the right, or a pad is under the buttocks, it will rotate the thorax such that the LAO projection is steeper and the detector caudal. This has to be compensated for during the set up for the angiogram. The clue in the former case is that more of the heart silhouette is over the spine.

The first step in setting up a cranial-LAO projection is to achieve the correct degree of steepness or shallowness. After that, the degree of cranial tilt has to be confirmed, so that the basal–apical septum is elongated. This can be estimated by seeing how much of the hemidiaphragm is superimposed over the cardiac silhouette – the more superimposition, the greater the cranial tilt. Additionally, the degree of cranial tilt can be determined by looking at the course of the ventricular catheter, it appearing to be foreshortened or coming directly at the viewer as the degree of cranial angulation is decreased (Figure 2.8).

Specific lesions

Ventricular septal defect (Figure 2.9)

The imaging of specific ventricular defects is beyond the scope of this review, but is commented upon in detail by various authors.[5] The injections to outline the septum and the lost margins which circumscribe the defect(s) are best performed in the left ventricle using a power injector. Two orthogonal (right angle) projections will give the best chance of profiling the lesion. However, pre-catheterization, the location of the defect should be well characterized by other imaging modalities, such that the projections chosen would give the optimal profile, with little modification. Table 2.1 lists single and biplane angulations for the various projections. For the perimembranous defect the mid-cranial LAO projection, at about 50° to 60° LAO, and as much cranial tilt as the equipment and patient position will allow (Figure 2.10) should be attempted. Additional projections can include a shallow-LAO with cranial tilt (so-called four-chamber or hepatoclavicular view) to outline the basal septum or inlet extension of a perimembranous defect. The RAO view will outline the high anterior and infundibular (outlet) defects.[6]

Coarctation of the aorta (Figure 2.11)

Biplane angiography should be used to outline the arch lesion. Projections that can be used include LAO/RAO,

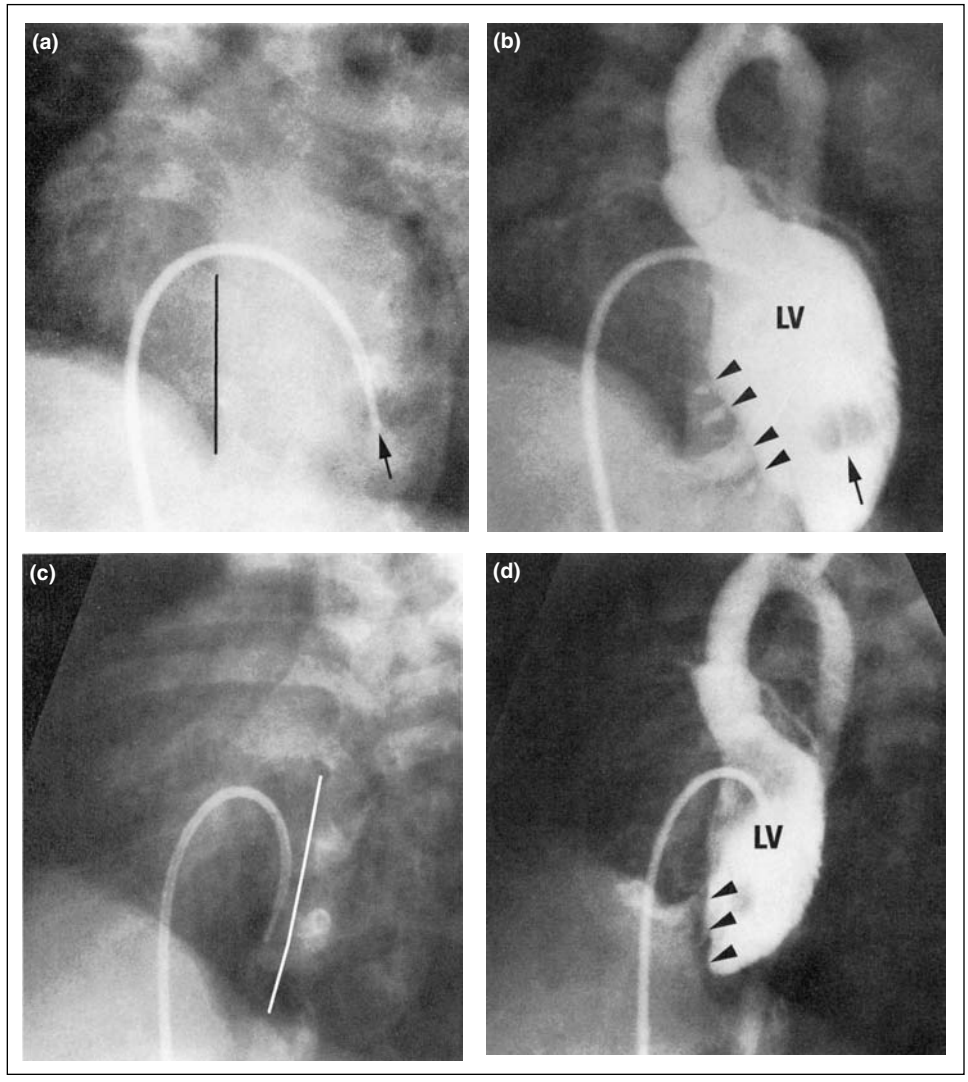

Figure 2.7
Achieving an LAO projection. (a) For a hepatoclavicular view, half of the cardiac silhouette is over or just left of the spine, with the catheter pointing toward the left of the image. (b) During the injection, the apex and catheter (arrow) will point toward the bottom and left of the image. In this example, the basal (inlet) portion of the septum is intact. Multiple mid-muscular septal defects are not well profiled (arrowheads). In (c) the LAO projection is achieved with the catheter pointing toward the bottom of the frame, and the cardiac silhouette well over the spine. During the contrast injection (d), the mid-muscular defects are now better profiled. (Modified from Culham[1] with permission.)

PA and LAT, or a shallow- or steep-LAO. Our preference is a 30° LAO and left-LAT, with 10° to 15° caudal tilt to minimize any overlapping structures, such as a ductal bump or diverticulum. Modifications to accommodate a right arch are generally mirror image projections (i.e., 30° RAO and left-LAT). The operator must be cautious to examine the transverse arch for associated hypoplasia, and this may be foreshortened in the straight left-LAT projection. In such an instance, for a left arch, a left posterior oblique projection may elongate the arch. This is particularly important if an endovascular stent is to be implanted near the head and neck vessels.

Aortic valve angiography (Figure 2.12)

Assessment of the diameter of the aortic valve in the setting of normally related great arteries with ventricular arterial concordance for balloon dilation is best performed using biplane in the long axis and RAO projections (Table 2.1).

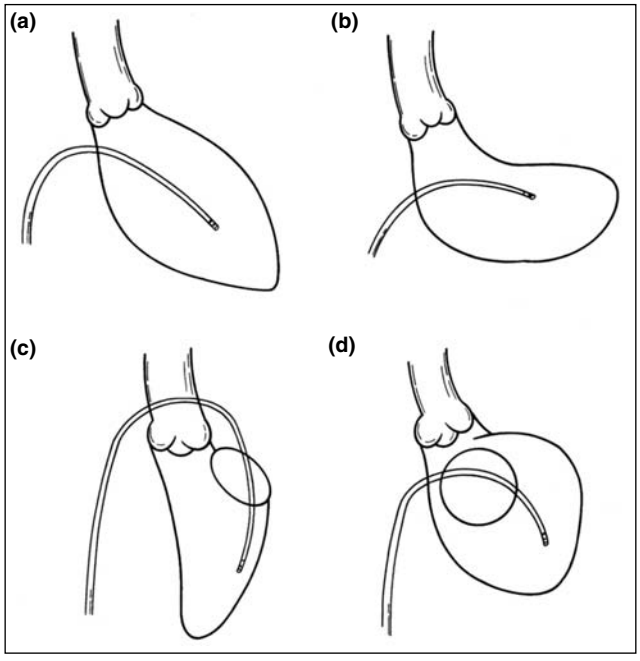

Figure 2.8
Obtaining the cranial tilt. In the standard RAO view, (a), the left ventricular apex points caudally and to the left. The LAO view will open the outflow from apex to base, as in diagram (c). If there is an upturned apex, as in Fallot's tetralogy, the RAO view will appear as in (b). Adding cranial tilt to a mid-LAO projection will not effectively open the apex to base projection, and the appearance will be as looking down the barrel of the ventricles, as in (d). (Modified from Culham[1] with permission.)

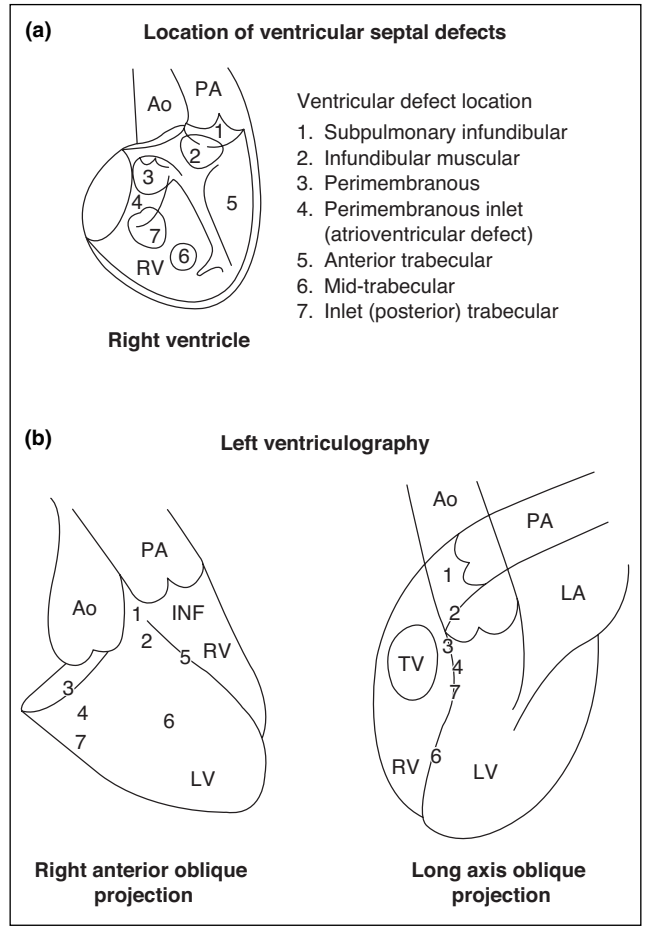

Figure 2.9
The locations of various ventricular defects are shown in panel (a) viewed from the right ventricle. In panel (b), the locations of these defects are noted as seen in an RAO or LAO projection.

Our preference is to obtain the diameter of the aortic valve from a ventriculogram, which profiles the hinge points of the leaflets. Caution must be observed when using an ascending aortogram, as one of the leaflets of the valve may obscure the margins of attachment.

The Mustard baffle (Figure 2.13)

Children who have had a Mustard operation may, over time, develop obstruction to one or both limbs of the venous baffle. As atrial arrhythmias are not uncommon in this population, particularly as adults, pacing systems are frequently required for management. In this regard, enlargement of a stenotic, although at times asymptomatic, superior baffle is frequently required. The optimum projection to outline superior baffle obstruction, for potential stent implantation, is a cranial angulated LAO projection (30° LAO and 30° cranial). This view will elongate the baffle pathway allowing accurate measurement prior to stenting. For inferior baffle lesions, a frontal projection will allow adequate localization of the lesion. Leaks along the baffle are more problematic, and require modification of the projection. The initial approach should be a PA projection, with modifications in angulation made thereafter to best profile the lesion for device implantation, not too dissimilar to that of Fontan fenestration closure.

The secundum atrial septal defect and the fenestrated Fontan (Figures 2.14 and 2.15)

Secundum atrial septal defects are best profiled in the 30° LAO with 30° cranial tilt. With the injection made in the right upper pulmonary vein, the sinus venous portion of the septum can be visualized, and anomalous pulmonary venous return ruled out. Additionally, any associated septal aneurysm can be outlined. With the application of transesophageal or intracardiac echocardiography, there is less fluoroscopic reliance on device positioning. When

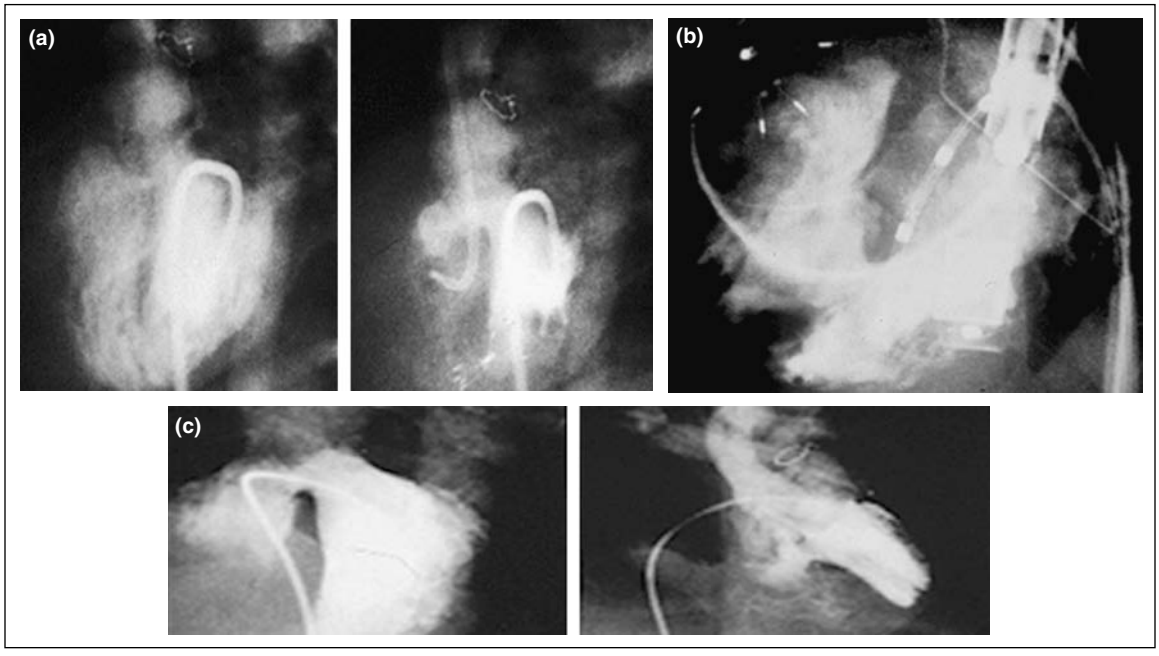

Figure 2.10
Panel (a) shows a left ventriculogram taken in the cranial-LAO projection. Note the apical, mid-muscular, and perimembranous septal defects. In panel (b), a modified hepatoclavicular view profiles a mid-muscular defect. Panel (c), left pane, is a left ventriculogram taken in the cranial-LAO view, with the catheter entering the ventricle through a perimembranous defect. Right pane, taken in the hepatoclavicular view with the catheter through the mitral valve, defines an inlet muscular defect, in a child with a pulmonary artery band.

balloon sizing is performed, this projection will elongate the axis of the balloon, for proper measurements.

The interventional management of the child with a fenestrated Fontan, whether a lateral tunnel or extracardiac connection, generally requires selective studies of the superior and inferior caval vein and pulmonary circulations, to determine the presence or absence of obstructive or hypoplastic pathways, and whether venous collaterals have developed. As such, they must be addressed by angioplasty, stenting, or embolization techniques before consideration of fenestration closure. Venous collaterals after an extracardiac Fontan will generally develop either from the innominate vein or from the right upper hepatic/phrenic vein, toward the neo-left atrium, less frequently from the right hepatic veins to the pulmonary veins. The optimum way to outline these lesions is in the AP and LAT projections, with selective power injections in the appropriate vessel. The location and dimensions of the fenestration may also be defined in these views, but for ideal profiling some degree of right or left anterior obliquity may be required.

The bidirectional cavopulmonary connection (Figure 2.16)

Second stage palliation for a number of congenital defects consists of a bidirectional cavopulmonary connection (aka, the bidirectional Glenn anastomosis). Because the caval to pulmonary artery connection is toward the anterior surface of the right pulmonary artery (rather than on the upper surface), an AP projection will result in overlapping of the anastomotic site with the pulmonary artery. Therefore, to determine whether the anastomosis is obstructed, a 30° caudal with 10° LAO projection will generally open that region for better definition. Furthermore, this projection will outline the full extent of the right and left pulmonary arteries. The left-LAT projection with or without 10° caudal angulation will profile the anastomosis for its anterior–posterior dimension. Contrast injection must be made in the lower portion of the superior caval vein. Examination of venous collaterals can be performed from the AP and LAT projections in the innominate vein.

Pulmonary valve stenosis, Fallot's tetralogy, and pulmonary valve atresia with intact ventricular septum (Figures 2.17 and 2.18)

Percutaneous intervention on isolated pulmonary valve stenosis was the procedure which assured in the present era of catheter based therapies. While angiographic definition of the right ventricular outflow tract and valve is not

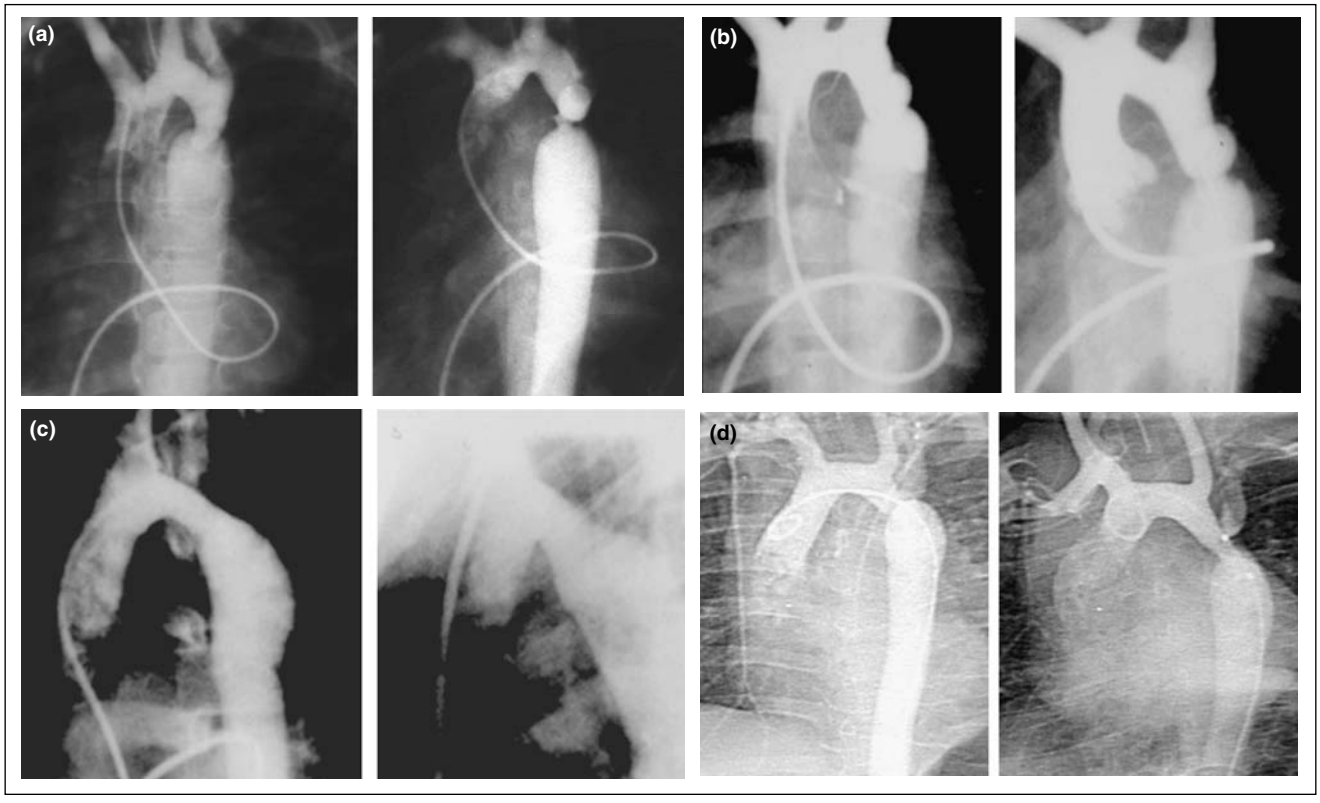

Figure 2.11
Panel (a), left pane, shows an ascending aortogram taken with a shallow-LAO projection without caudal angulation. The catheter was placed through a transeptal entry to the left heart. While the area of the coarctation can be seen, it is the caudal angulation which identifies the details of the lesion, including a small ductal ampulla, right pane. In panel (b), similar information is obtained, by employing caudal angulation to the frontal detector, right pane, while in the shallow-LAO projection in contrast to that information obtained without caudal angulation, left pane. In panel (c), left pane, hypoplasia of the transverse arch can be identified. However, in contrast, in the right pane, the degree of foreshortening is obvious. Panel (d), right pane, shows the standard LAO projection of an ascending aortogram. In this case there is overlap of the area of obstruction, transverse arch hypoplasia, and stenosis of the left subclavian artery, not defined until cranial angulation is employed, right pane.

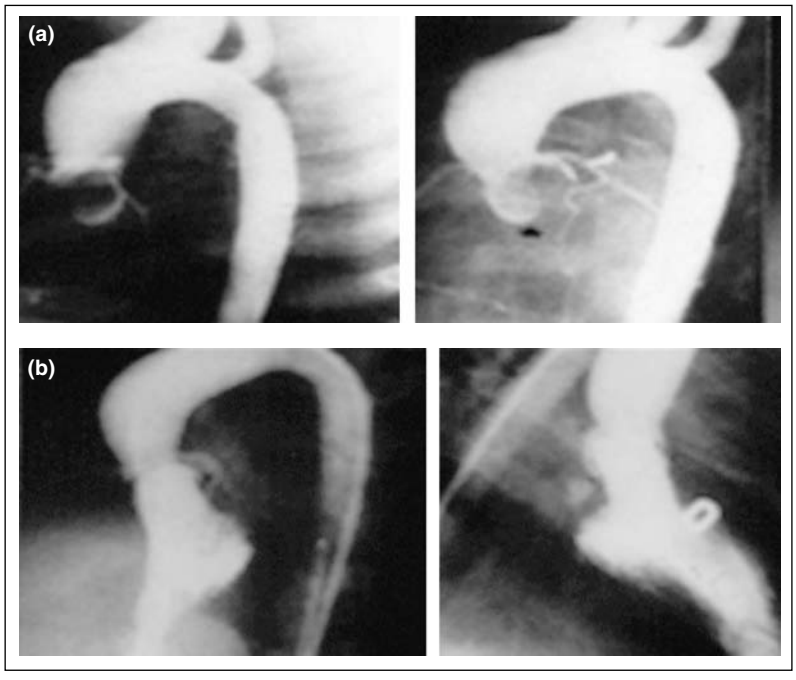

Figure 2.12
Intervention on the aortic valve requires accurate definition of the hinge points of the leaflets. In panel (a), long axis oblique views from an ascending aortogram do not define the margins of the leaflets due to overlap of the cusps (bicuspid in these examples). In panel (b), long axis oblique (left) and RAO views, the left ventriculogram allows easier identification of the leaflet hinge points, where measurements can be made.

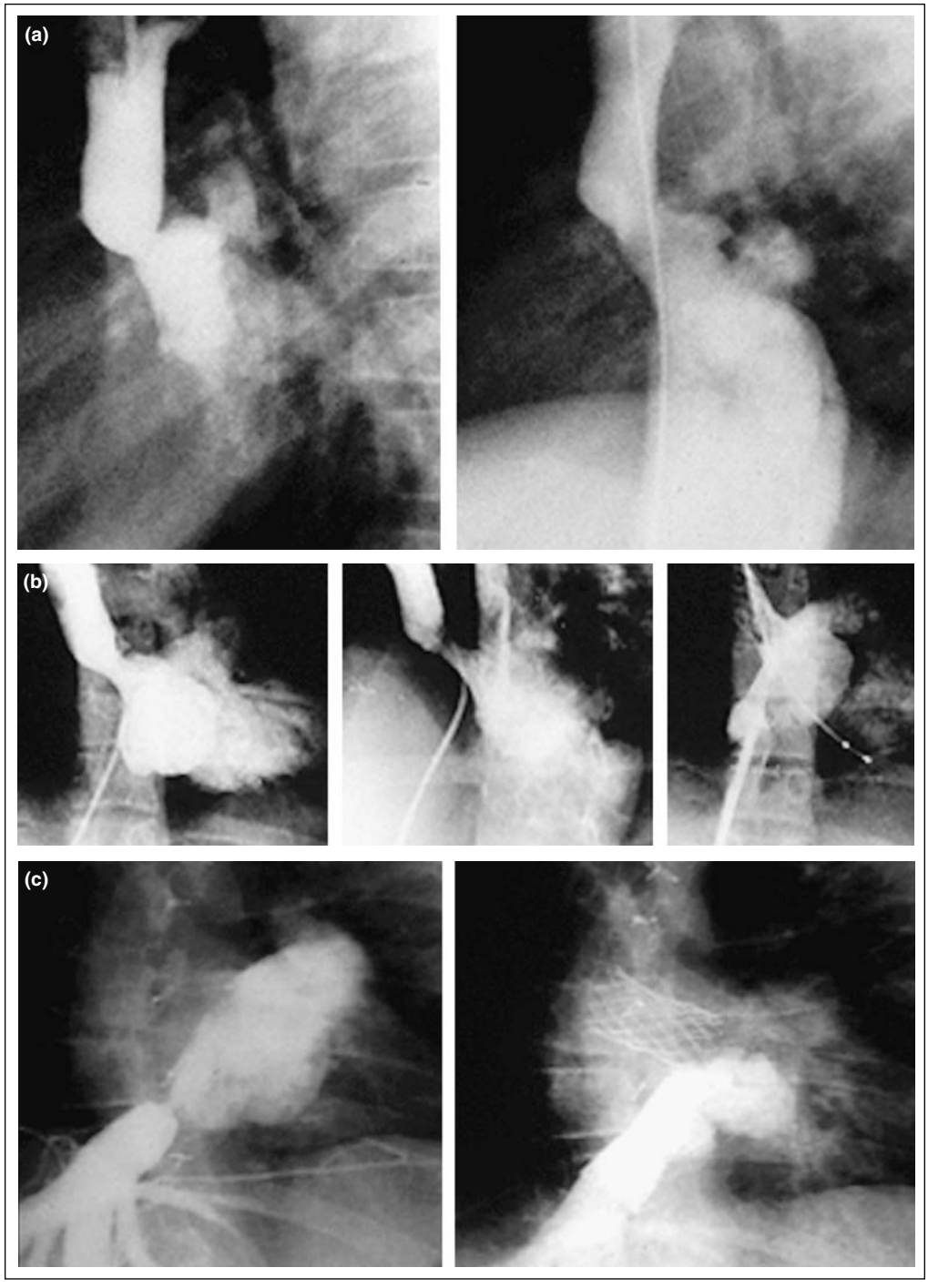

Figure 2.13
Baffle obstruction after a Mustard operation is, as the population ages, an increasingly common event. This is particularly so, with the need to manage such patients with transvenous pacing devices. In panel (a), left pane, the presence of a superior baffle obstruction can be identified from the left-LAT projection. However, only with cranial angulation (cranial-LAO view, right pane) will the full extent of the lesion be detailed. This is particularly critical, as shown in panel (b), where the frontal view, left pane, does not show the full extent of the obstruction, and only from the angulated view will the length and diameter of the lesion be outlined (middle pane). A stent is placed, followed by a transvenous pacing system, shown in the right pane from a frontal projection. For an inferior baffle lesion, the frontal (PA) projection is optimal, panel (c), before (left) and after (right) a stent is placed.

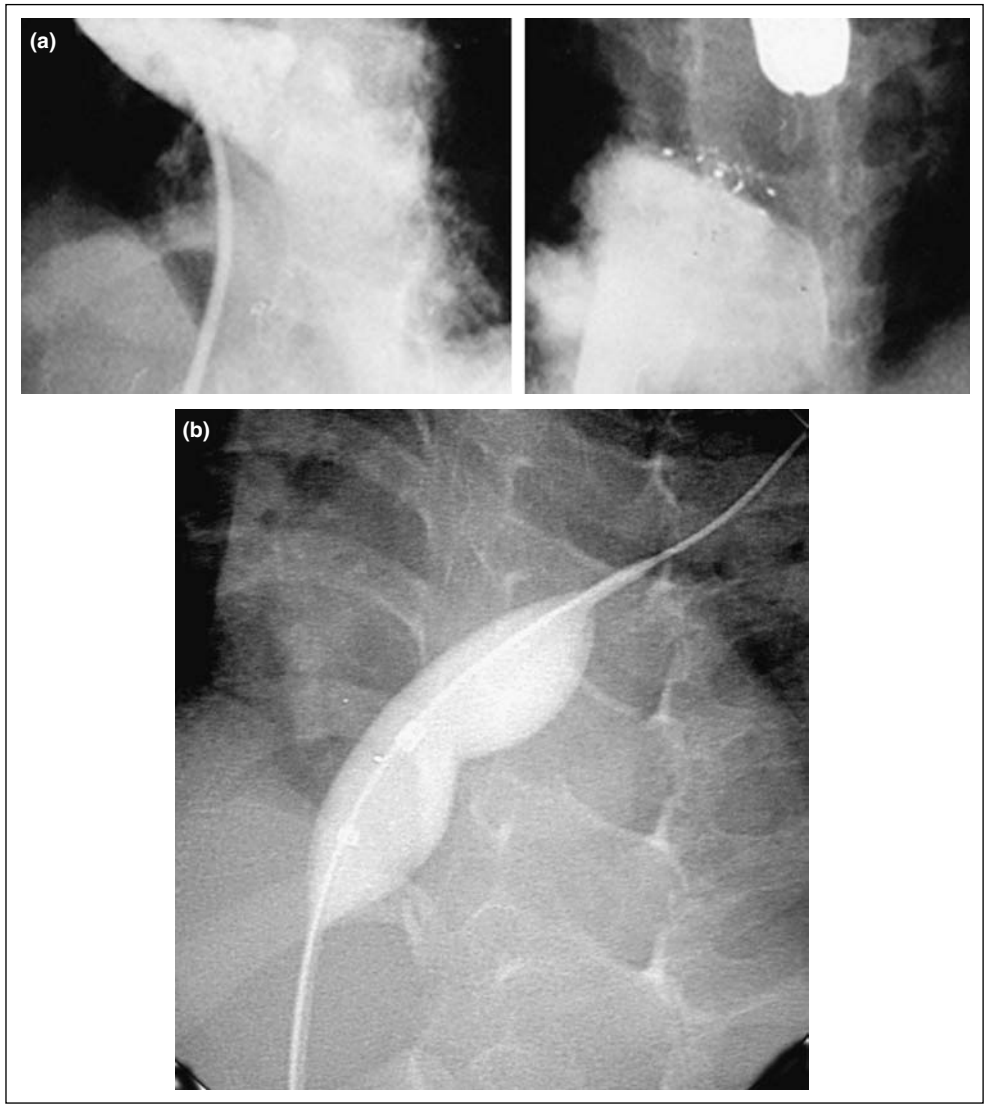

Figure 2.14
Use of angiography for septal defect definition and device placement in the setting of a secundum atrial septal defect has been supplanted by intracardiac and transesophageal techniques (panel a). However, fluoroscopy is still required for initial device localization, and in many laboratories a short cine-run records the diameter of the static balloon diameter to choose the device size. In this case, we find the 30° LAO with 30° cranial tilt best to elongate the balloon to avoid foreshortening (panel b).

complicated, several features must be kept in mind when approaching the angiography for an interventional procedure. In the case of isolated pulmonary valve stenosis, and other right ventricular outflow tract lesions, because the outflow tract can take a horizontal curve, a simple AP projection will foreshorten the structure. Therefore, a 30° cranial with 15° LAO will open up the infundibulum, and allow visualization of the valve and the main and branch pulmonary arteries. The best definition of the hinge points of the valve, to choose the correct balloon size, is from the left-LAT projection. Occasionally, 10° or 15° caudal angulation of the LAT detector can be used to separate the overlap of the branch vessels seen on a straight left-LAT projection. However, this is not recommended, as it will also foreshorten the outflow tract and the valve will appear off plane, giving incorrect valve diameters.

Branch pulmonary artery stenosis (Figures 2.19–2.21)

Pulmonary artery interventions are most common, and represent the most difficult angiographic projections to separate out individual vessels for assessment and potential intervention. A cranially tilted frontal projection with a left-LAT or RAO/LAO projections is frequently the first

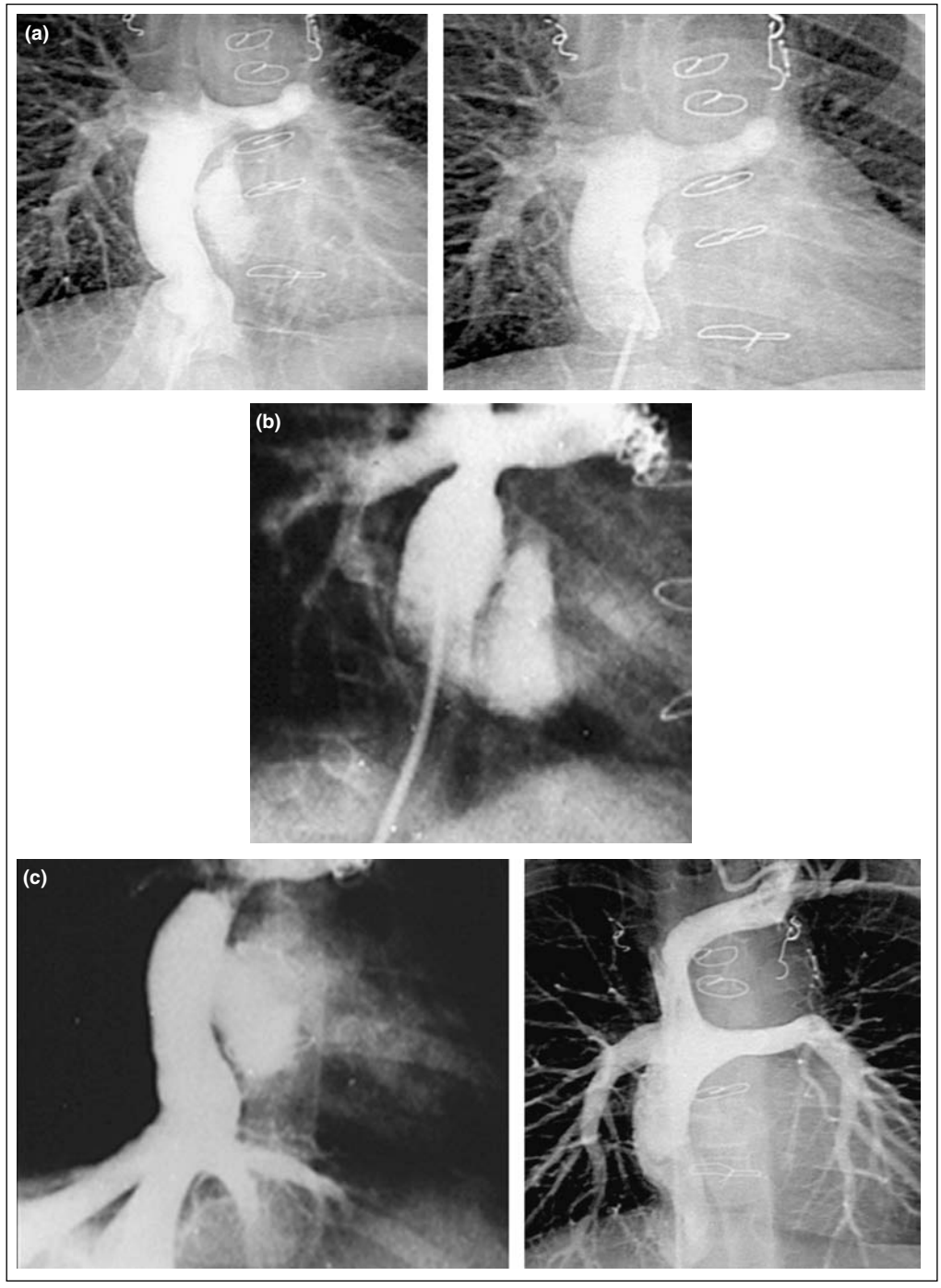

Figure 2.15
Panel (a) shows the appearance of a fenestrated extracardiac Fontan in the frontal projection, and its appearance after device closure. Generally, a frontal projection profiles the defect adequately, but at times some angulation is required, as seen in panel (b), where the defect is best profiled in a shallow-RAO view. Also note coils in the left superior caval vein which developed after the Fontan procedure and required embolization. Occasionally, collateral vessels develop from the hepatic/phrenic vein (panel c, left) or innominate vein (panel c, right), where coils have been placed. The primary view being frontal (PA) and left-LAT.

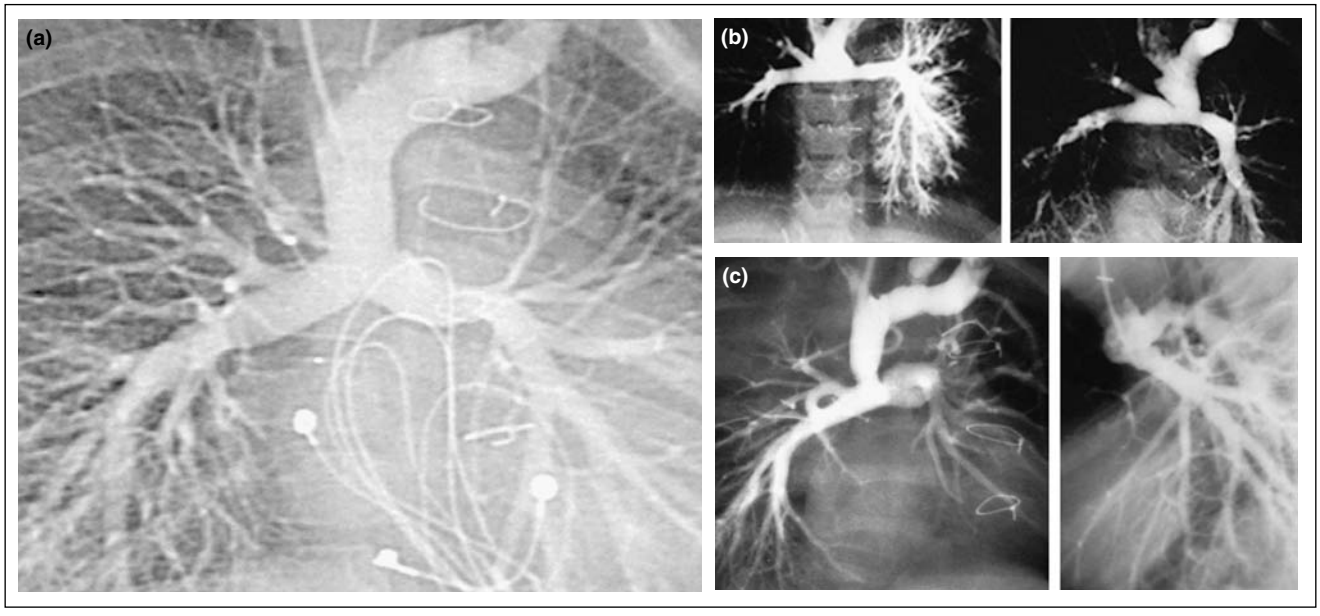

Figure 2.16
Because of an offset in the anastomosis between the superior caval vein and right pulmonary artery, the optimal view to see the anastomosis without overlap is a shallow with caudal tilt, as seen in panel (a). Panel (b), left pane, is in the frontal projection, where overlap of the anastomosis obscures a potential lesion, as seen in the angulated view, right pane. The combination of an angulated frontal detector and caudal angulation of the lateral tube will allow definition of the anastomosis (left pane) and the pulmonary artery confluence (right pane), panel (c).

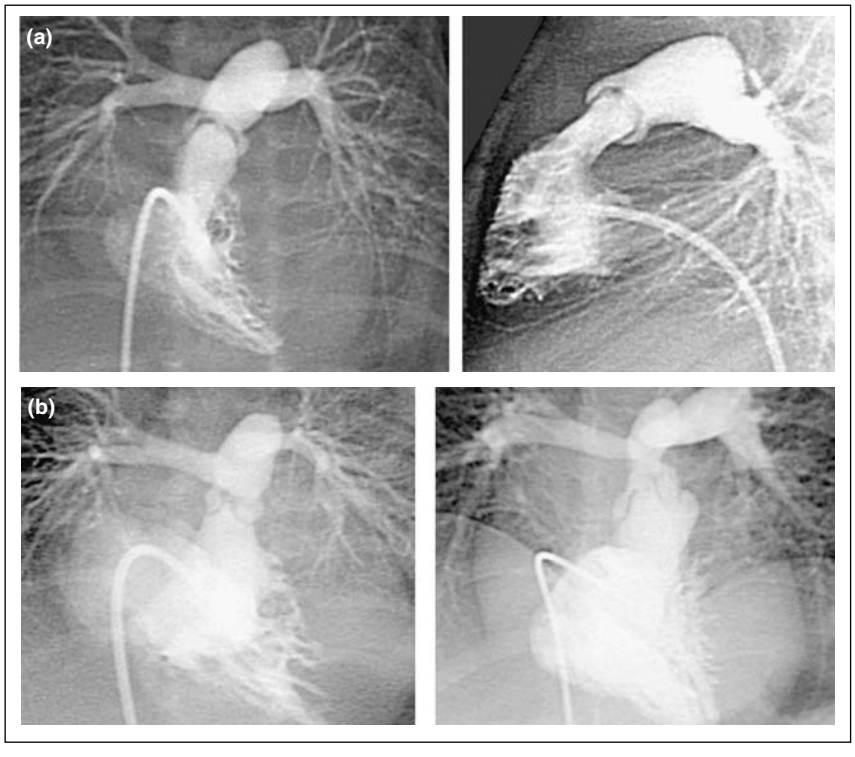

Figure 2.17
Panel (a) depicts a case of typical isolated pulmonary valve stenosis in a neonate. The outflow tract is profiled in the cranially angulated frontal projection, with a slight degree of LAO angulation (left pane). The right ventriculogram outlines the form of the ventricle, the main pulmonary artery (and ductal bump) as well as the pulmonary artery confluence, and branch dimensions. The LAT view (right pane) outlines the valve leaflets (thickened and doming) and allows accurate delineation of the valve structures for balloon diameter determination. In panel (b), two right ventriculograms in the cranially angulated slight LAO view depict the size of the annulus and main and branch pulmonary arteries (typical valve stenosis with left pulmonary hypoplasia, left pane; dysplastic valve stenosis, small non-dilated main pulmonary artery and proximal left branch pulmonary artery stenosis with post-stenotic dilation, right pane).

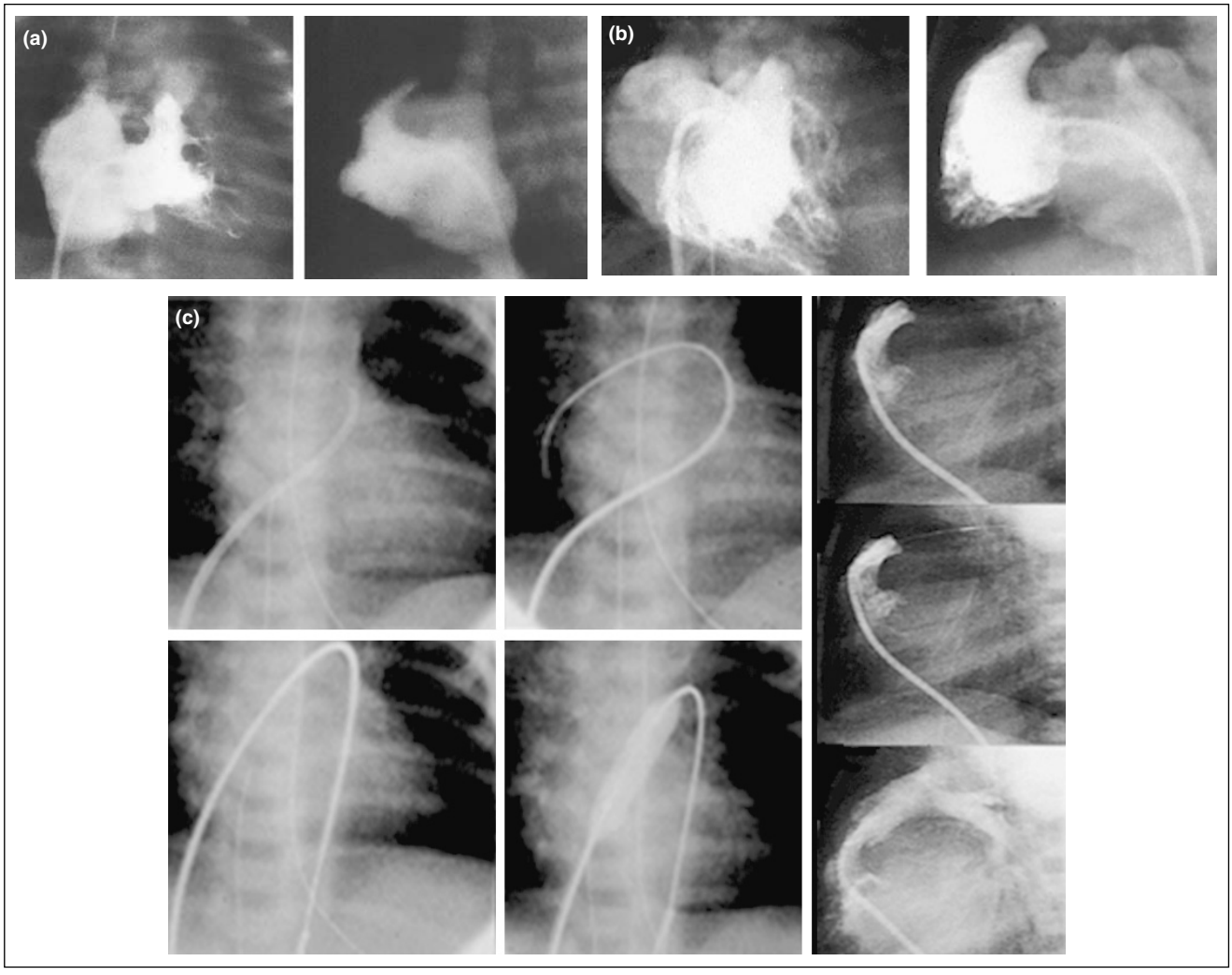

Figure 2.18
Angiographic projections for intervention in pulmonary atresia with intact septum are similar to that of isolated pulmonary valve stenosis. In panels (a) and (b), cranial angulation is critical to image the valve plate (left panes), while a left-LAT will suffice for imaging the anterior–posterior aspects of the outflow tract. In valve perforation, it is critical to have visual control in 2 orthogonal planes, to avoid inadvertent infundibular perforation. A series of images during valve perforation is seen in panel (c). The left upper pane shows the catheter position; right upper pane, perforation and wire in the right pulmonary artery; left lower pane, the wire guide across the duct for stability; and in the right lower pane, balloon dilation of the valve. In the accompanying panel, viewed from the left-LAT projection, is a series of images taken during perforation: top pane, position confirmation; middle pane, radiofrequency perforation; lower pane, angiography in the main pulmonary artery.

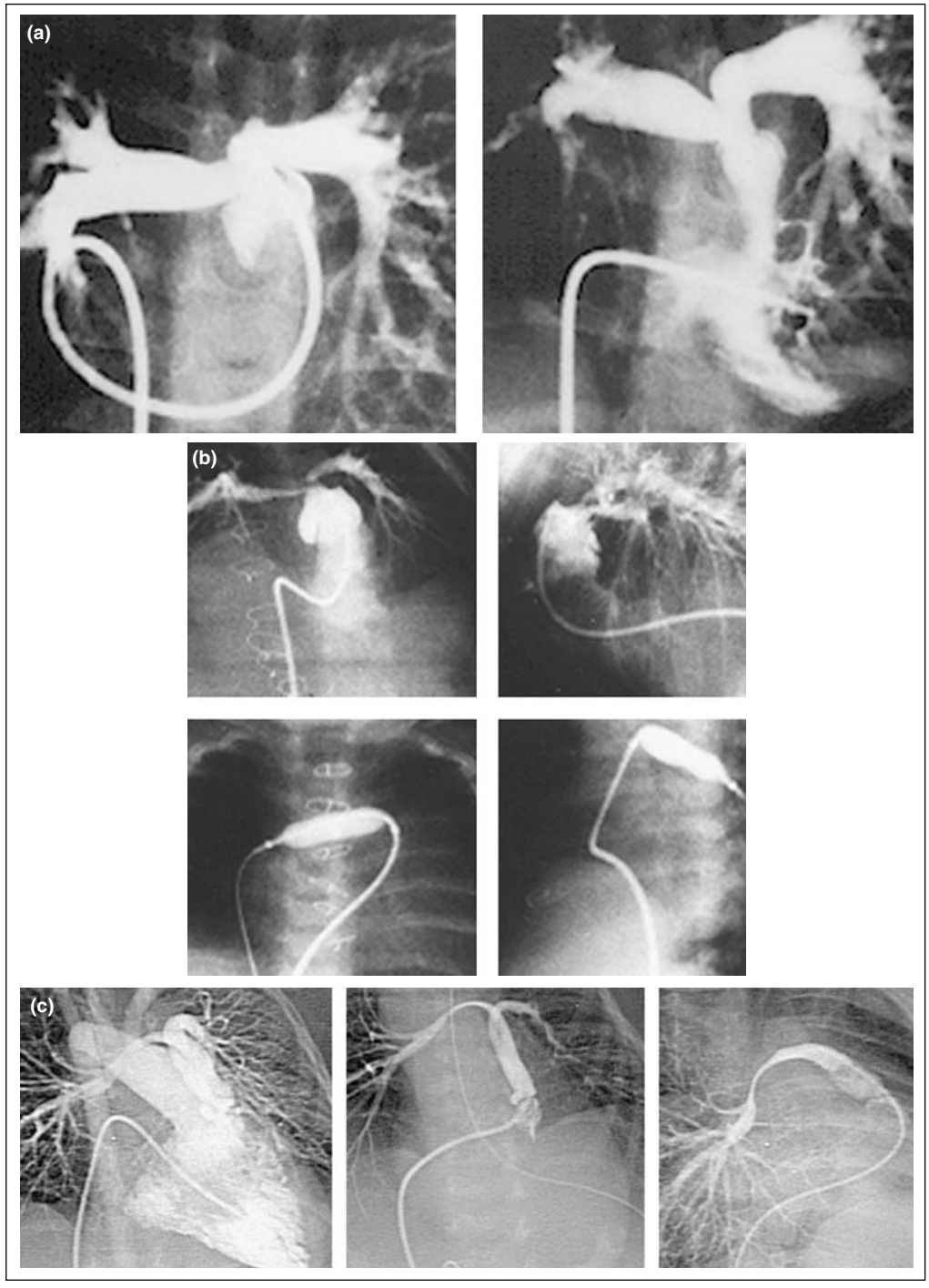

Figure 2.19
Angiography for selective intervention on the branch pulmonary arteries can be most difficult due to overlapping of structures. No single projection is totally representative and frequently multiple views are required. In panel (a), left pane, a scout film is taken in the main pulmonary artery, and in the right pane, the right ventricle. Both images are taken in the cranial-LAO projection and, in these examples, clearly outline the outflow tracts and branch confluences. In panel (b) the dilated main pulmonary artery would have obscured the branch pulmonary artery confluence, and this cranial-LAO (left upper pane) and caudal left-LAT (right upper pane) nicely details the anatomy for subsequent intervention (lower panes). In panel (c), ventriculography obscures the details of the crossed pulmonary vessels (left pane), while selective injection in the cranial (middle pane) and RAO (right pane) projections details the anatomy.

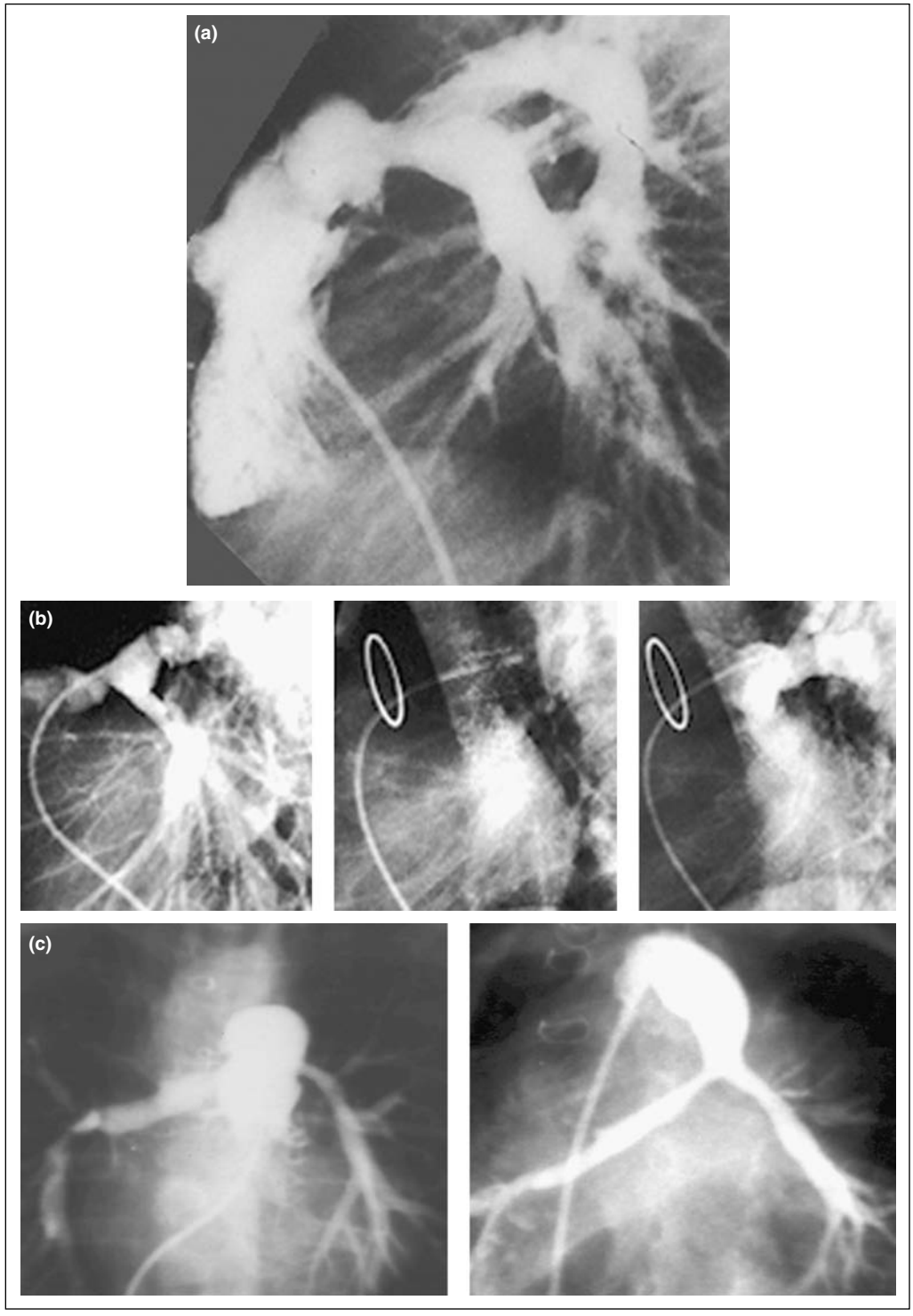

Figure 2.20
In panel (a), the image is taken from a left-LAT projection with caudal tilt. This will separate the proximal right and left pulmonary artery branches, and detail the main pulmonary artery. The outflow tract is foreshortened, and this view will mislead the operator when examining the diameter of the valve, and infundibulum. If such detail is required, a straight left-LAT should be performed. In the caudal-LAT projection, the left pulmonary branch will sweep superiorly and towards the upper right corner of the image, while the left pulmonary artery will appear more medial and in the center of the image. In panel (b) the child had severe bilateral branch stenosis (left pane), which persisted after surgical repair and valve insertion. Using the left-LAT view, stents could be placed in each branch (middle and right panes). In panel (c), severe main pulmonary artery dilation has obscured the confluence and very hypoplastic pulmonary arteries (left pane) in this child shortly after surgery. In this case, steep caudal angulation of the frontal tube with 10° or 15° LAO has detailed the lesion for the intervention (right pane).

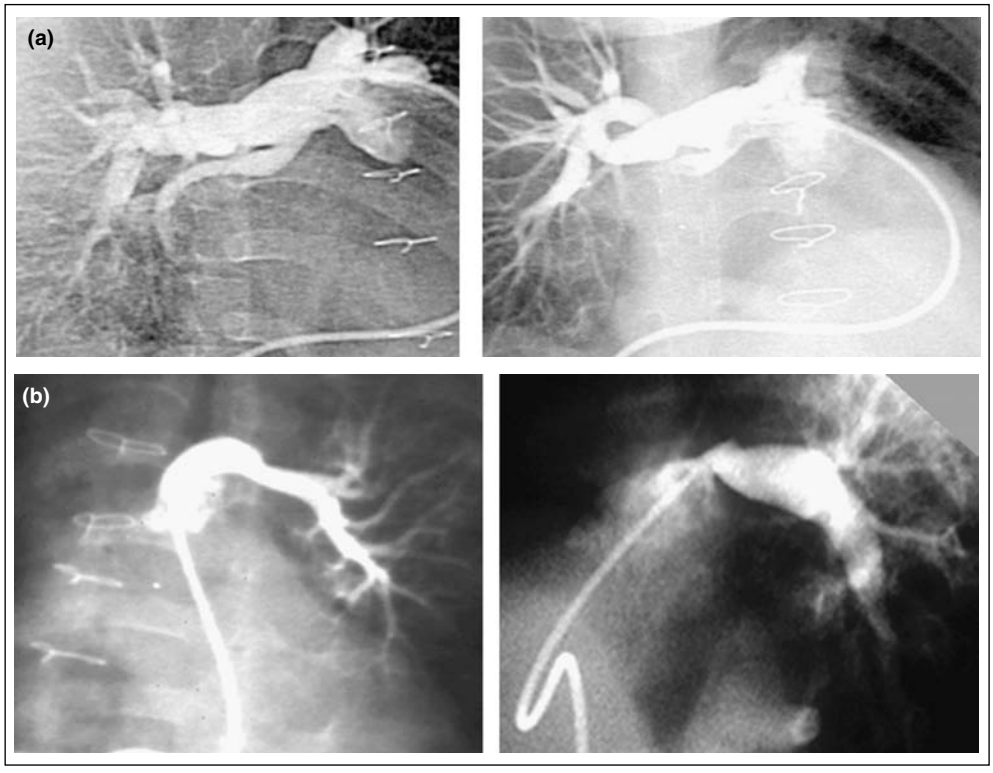

Figure 2.21
Selective injection into a branch pulmonary vessel will give the best detailed image. Overlap of the intrahilar branching vessels, however, will interfere with interpretation of the lesion as seen in panel (a), left pane, taken in the RAO projection. By adding caudal tilt, as in this example, the tortuous path of the intrahilar vessel can be seen. In panel (b) (left and right panes), cranial-LAO projections detail the length of the left pulmonary artery and proximal areas of potential stenosis.

series of views that can be performed, as scout studies to map the proximal and hilar regions of the pulmonary circulation. The injection may be performed in either the ventricle or main pulmonary artery. Since there is frequent overlap as seen in viewing the right ventricular outflow tract (see above), these standard views can be modified by increasing or decreasing the degree of RAO or LAO, and adding caudal or cranial tilt. Selective branch artery injections are best for detailed visualization, to plan the intervention. For the right pulmonary artery, a shallow-RAO projection with 10° or 15° cranial tilt will separate the upper and middle lobe branches, while a left-LAT with 15° caudal tilt will open up all the anterior vessels. Similarly, to maximize the elongated and posterior leftward directed left pulmonary artery, a 60° LAO with 20° cranial is very effective, with a caudal tilt on the lateral detector. Occasionally, in small babies after surgical reconstruction of the branch pulmonary arteries, the main pulmonary artery is aneurysmal and obscures the confluence. In this case, a steep 30° caudal projection with the frontal detector with 10° to 20° RAO will open up the bifurcation.

Summary

This short introduction to interventional angiography will allow the reader a point of departure to visualize the most common lesions. However, many cases occur that do not fall into a standard categorization and the operator must be prepared to alter the imaging projection to optimally define the lesion. Successful outcomes require patience, perseverance, and the learned experience of others.

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3

Transesophageal echocardiographic guidance of transcatheter closure of atrial septal defects

Charles S Kleinman

During the past several years the cardiac catheterization laboratory has evolved from a primarily diagnostic venue into a setting in which cardiac therapy is provided to patients with a large variety of congenital cardiac malformations. To some extent, the decreased number of diagnostic procedures is related to the availability of alternate means of assessing cardiac anatomy and physiology, including echocardiography and magnetic resonance imaging. Echocardiography has also evolved as a technique for providing an imaging modality that is, at once, complementary to angiography and fluoroscopic imaging, while providing unique imaging that allows radiolucent structures such as the atrial and ventricular septum and intracardiac valves to be imaged. Such images may be critical for the assessment of the candidacy of patients who are referred for transcatheter treatment of atrial or ventricular septal defects, and may also be used to monitor the placement of devices for the closure of these defects.

In the late 1980s the introduction of the Rashkind atrial septal defect closure device offered the potential for a relatively non-invasive option for the closure of ostium secundum atrial septal defects. It was immediately recognized, however, that the effort to replace a relatively safe and well established surgical procedure with a new, and untried, transcatheter therapy would only be acceptable if the attendant risks could be minimized.

That device consisted of multiple wire 'legs' with fish-hook-like ends for anchoring on the atrial septum, at the rim of the defect. The fish-hooks made placement of the device a harrowing experience, and made dislodgement of the devices an unacceptable risk. For this reason, we argued that visualization of the size and position of the defect within the atrial septum, and assurance of appropriate placement within the atrial septum, with adequate clearance from neighboring structures such as the atrioventricular valves or pulmonary venous entry, would be advisable.[1] In the years since, transesophageal (TEE) and intracardiac echocardiography (ICE) have evolved as essential components of the interventional catheterization protocol for the guidance of transcatheter closure of atrial septal defect.[1–27]

The purpose of this chapter is to discuss the echocardiographic findings that identify patients who are candidates for transcatheter closure of an atrial septal defect. The anatomic features of an atrial septal defect that is 'closable' by device and the use of TEE for the guidance of these procedures will be described.

The potential availability of a 'less invasive' means of defect closure than open heart surgery might well tempt referring physicians to relax the criteria for referral of patients for defect closure. Nonetheless, the criteria for referral for transcatheter closure of atrial septal defect should include whether the patient would otherwise have been referred for surgical closure. This includes the detection of physical findings suggestive of right heart volume overload, including a right ventricular impulse at the lower left sternal border, and murmurs consistent with relative pulmonary and tricuspid stenosis. Symptoms are almost never a characteristic of atrial septal defect during early childhood, and almost always are reserved for patients in the 40+ age group. In infancy, atrial septal defect may complicate the management of patients with chronic pulmonary insufficiency, including bronchopulmonary dysplasia. Echocardiographic findings that characterize a 'significant' atrial septal defect include right atrial and right ventricular dilation, and secondary to left-to-right atrial shunting. In addition, the motion of the ventricular septum is often paradoxical. The latter is secondary to contraction of the ventricular muscle mass toward the center of mass. The latter may be displaced toward the left ventricular side of the septum in cases of

significant right ventricular volume overload. In such cases the ventricular septum may move toward the right ventricular free wall during systolic contraction.

Two-dimensional echocardiography may be used to visualize the position of the atrial defect within the atrial septum. The characteristics of an atrial septal defect that is potentially 'closable' by device include an ostium secundum defect, in the position delineated by the fetal fossa ovalis. The 'closable' defect characteristically has an adequate rim to separate the defect from the orifice of the right upper pulmonary vein in the left atrium, the posterior wall of the atrial septum, the orifices of the superior and inferior vena cava in the right atrium, the atrioventricular valves, and the retroaortic rim, behind the aortic root.[28]

Typically, the rims of the atrial septal defect may be evaluated from subxiphoidal and transthoracic imaging windows, or through the use of multiplane transesophageal imaging. Intracardiac echocardiography may provide imaging of the atrial defect, and may allow individual rims to be examined. The ICE approach may be particularly effective for imaging of the posteroinferior rim of the ostium secundum atrial septal defect, near the insertion of the inferior vena cava to the right atrium. Transesophageal echocardiography provides a more extensive anatomic image of the atrial septum than does intracardiac echocardiography.[11,29–33]

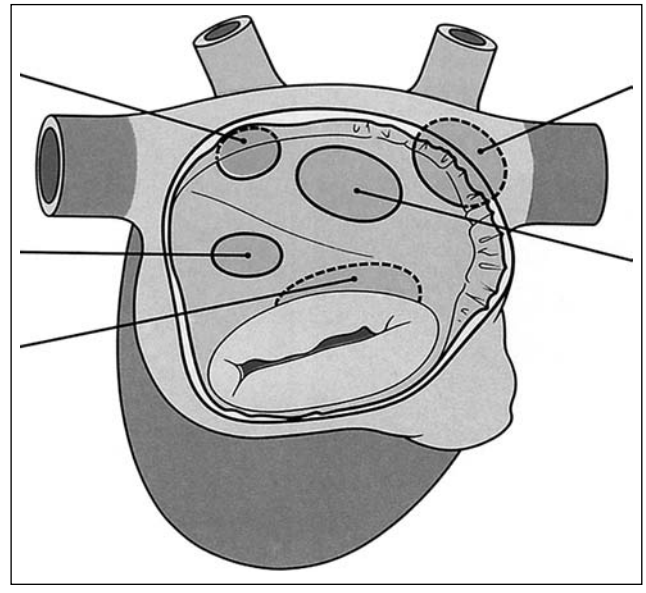

Figure 3.1
Schematic diagram of the right atrial aspect of the atrial septum, with the locations of various forms of atrial septal defect demonstrated. Ostium secundum defects, at the site of the fetal foramen ovale, are the only defects that are considered potentially 'closable' using currently available devices (SSV, superior sinus venosus; ISV, inferior sinus venosus; CS, coronary sinus; ostium 1°, ostium primum; ostium 2°, ostium secundum). Note the proximity of the inferior and superior sinus venosus defects to the respective vena caval insertions to the right atrium. The superior sinus venosus defect is virtually always associated with partially anomalous drainage of the right pulmonary vein. The coronary sinus defect is associated with the entry of the coronary sinus to the right atrium, and is almost always associated with persistent drainage of a left superior vena cava, and some degree of coronary sinus unroofing. The ostium primum defect is at the central fibrous body, with close proximity to both atrioventricular valves. (Reproduced from Anderson et al[34] with permission.)

Anatomic characteristics

The ostium secundum atrial septal defect represents a persistently patent defect at the site of the fetal fossa ovalis.[34–38] This is anatomically distinct from the superior or inferior sinus venosus defect. The latter represent defects of the venae cavae. The superior sinus venosus defect is commonly associated with partial anomalous drainage of the right upper pulmonary vein, which usually enters the superior vena cava. Defects of the coronary sinus usually involve partial unroofing of the coronary sinus, with potential right-to-left shunting at this level, with persistent drainage of the left superior vena cava to the coronary sinus. Ostium primum atrial septal defects are a form of atrioventricular septal defect, with the defect at the lower aspect of the atrial septum, immediately above the ventricular septum. These defects characteristically are associated with abnormalities of the atrioventricular valves, including a cleft of the septal leaflet of the mitral valve (Figure 3.1).[34–36]

The remainder of this chapter will focus on the characteristics of the fossa ovalis and ostium secundum atrial septal defect that render such defects candidates for transcatheter occlusion. It should be noted, for example, that the superior rim of the fossa ovalis represents an infolding of the junction between the superior vena cava and the right upper pulmonary vein, rather than a true 'secondary septum' (Figure 3.2). This infolding abuts the aortic root (Figure 3.3 and Figure 3.4).

Characterizing a defect 'closable' by device

The characteristics of a defect defined as 'closable' by device have evolved with increasing experience and with alterations in device design. Using the 'Clamshell' or 'Star-Flex' devices, which consist of two sets of articulated wire arms, with Dacron patches, connected by a central wire 'post,' small to moderate defects, in a central position within the atrial septum, could be closed. Devices were chosen that

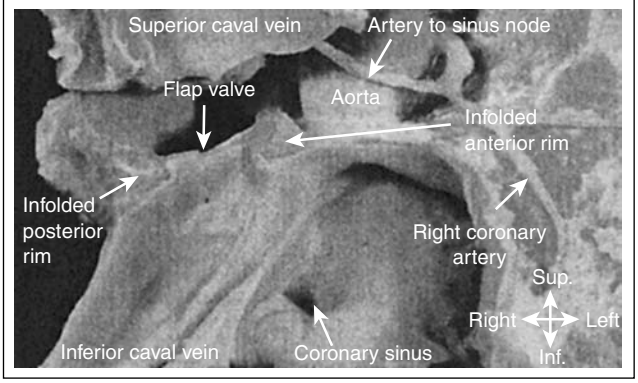

Figure 3.2
Development of the atrial septum includes an infolding of the atrial roof, at the superior aspect of the atrial septum. This area, near the aortic root, does not represent true septal formation, and results in a potential space between the superior and anterosuperior aspect of the atrium and the aorta. (Reproduced from Anderson et al[29] with permission.)

were twice the diameter of the defects to be closed. This two-to-one ratio of diameters imposed limitations on the size of the defects that could be closed. Such devices are not 'self centering,' within the atrial defects. The devices closed the defects through apposition of the two sets of wire arms to the opposing sides of the septal rims of the defects. Thus, it was initially thought that only secundum defects of less than 20 mm diameter would be closable by devices. It has subsequently been accepted that, with the use of devices that close defects through the use of a central 'stent' with apposing disks, defects approaching 40 mm in diameter and those with rim deficiencies in the retroaortic (anterosuperior rim) area could also be closed.

The latter design, introduced by AGA Medical Corporation as the Amplatzer Atrial Septal Occluder® (ASO), includes a central stent within the atrial septal defect. The disks on either side of the central occluder anchor the device in place. The 'size' of the device is defined as the central stent diameter, in mm. The disks on either side extend 6–8 mm beyond the margins of the central occluding stents.

The rims of septum surrounding the ostium secundum atrial septal defect are defined as superoposterior (superior vena caval), inferoposterior (inferior vena caval), inferior (atrioventricular valve), posterior, and anterosuperior (retroaortic).[39]

Transesophageal imaging of atrial septal defect

Utilizing the multiplane TEE probe, ostium secundum (Figure 3.5) defects may be characterized[40] Figueroa et al (Table 3.1) have defined the angulation required to visualize the rims surrounding these defects. Multiplane imaging has been defined as important, predominantly for providing adequate imaging of the anterosuperior (retroaortic) rim of the defect, with a median TEE angle of 34°, with a range from 0° to 98°.

The anatomic characteristics of the ostium secundum atrial septal defect have been defined by Podnar and associates, who examined 190 consecutive patients who presented for consideration for transcatheter treatment (Table 3.2).[39]

Centrally placed defects, without rim deficiency, represented only 24.2% (46) of these patients, whereas 42.1% (80) had deficiency of the retroaortic (superoanterior) rim. Most centers do not consider retroaortic rim deficiency to represent an absolute contraindication to device placement. Deficient inferoposterior (inferior vena caval) (10%), inferoposterior and posterior (2.1%), inferoanterior (1%), and coronary sinus (1%) rim would be considered by many centers to be contraindications to device placement.

Transesophageal echocardiographic monitoring of atrial defect closure

Recently, reports have focused attention on the potential for late erosion of the atrial septal wall, following transcatheter closure of atrial septal defect.[41] These erosions have occurred at varying intervals, ranging from hours to 3 years, following device placement, and have been associated with varying degrees of hemodynamic embarrassment, ranging from aorto-atrial fistulas to hemopericardium with acute tamponade and death.[42] The incidence of these late complications appears to be in the range of 0.1%. After a careful review of the reported cases of late atrial erosion with the Amplatzer ASO, a review board concluded that the region most 'at risk' for late erosion is the retroaortic rim, where erosion may occur into the region representing the fold in the roof of the atrium, that is interposed between the superior vena cava and right superior pulmonary vein, and the aortic root. It was determined, however, that while anterosuperior rim insufficiency may be necessary for such erosions to occur it is not, in and of itself, sufficient to account for them. It appears that a necessary component is oversizing of the device used for defect occlusion. Such oversizing appears to have become a frequent occurrence following general availability of the Amplatzer ASO, probably relating to the desire of operators to avoid the potential for device embolization, and initial ignorance of the risk for late erosion.[41] The review board has, therefore, re-emphasized the importance of TEE monitoring of device placement. TEE is used to locate the defect and to evaluate the sufficiency of the inferoposterior, inferior, and superoposterior

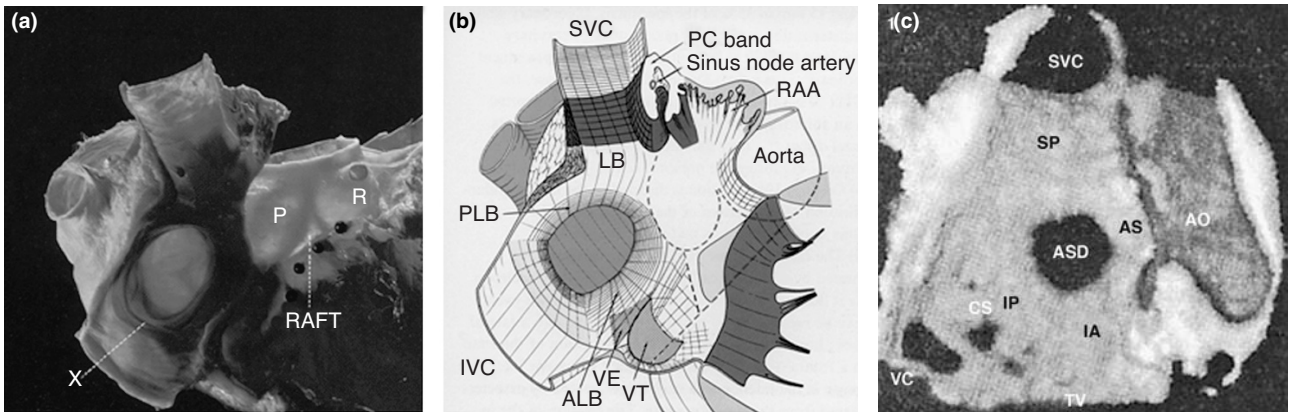

Figure 3.3
Transilluminated, waxed specimen, demonstrating right atrial aspect of the atrial septum, with three-dimensional rendering of same (a,b). Note the relationship between the region of the foramen ovale (X) and the aortic posterior sinus of Valsalva. CS, coronary sinus; IVC, inferior vena cara; LV, left ventricle; MS, membranous septum; P, posterior sinus of Valsalva; PT, pulmonary trunk; R, right sinus of Valsalva; RIPV, right inferior pulmonary vein; RPA, right pulmonary artery; RSPV, right superior pulmonary vein; RV, right ventricle; TS, transverse sinus; Valvula F ovalis, Valvula fossa ovalis. (Reproduced from McAlpine[23] with permission.) Part (c) is a reference figure for comparison with the three-dimensional echocardiographic reconstruction of the atrial septum, to the right. Note the position of the atrial septal defect (ASD), and the relationship to the superior vena cava (SVC), the inferior vena cava (IVC), the coronary sinus (CS), and the aortic root (AO). The superior vena caval rim of the ASD is also referred to as superoposterior (SP), the inferior vena caval rim of the ASD is also referred to as inferoposterior (IP). The atrioventricular valve rim of the defect, near the tricuspid valve (TV), is also referred to as the inferoanterior (IA) rim, whereas the retroaortic rim of the defect is also referred to as the posteroanterior (PA) rim of the defect.

Table 3.1 *Multiplane TEE – imaging angle and structures seen (Reproduced from[34] with kind permission of Springer Science and Business Media.)*

	TEE angle	
Rim	Median (°)	Range (°)
Superior vena cava	92	78–126
Inferior vena cava	90	51–126
Tricuspid valve	0	0–60
Mitral valve	0	0–18
Right upper pulmonary vein	0	0–69
Posteroinferior rim	90	0–120
Anterior (aortic) rim	34	0–98

Table 3.2 *Atrial septal defect morphology in 190 consecutive patients*

Morphology	Number (%) patients
Centrally placed defect	46 (24.2)
Deficient superior anterior rim	80 (42.1)
Deficient inferior posterior rim	19 (10.0)
Perforated septal aneurysm	15 (7.9)
Multiple defects	14 (7.3)
Deficient IA and SA rim	6 (3.1)
Deficient IP and posterior rim	4 (2.1)
Deficient inferior anterior rim	2 (1.0)
Deficient superior posterior rim	2 (1.0)
Deficient coronary sinus rim	2 (1.0)
Total	190 (100)

Source: Podnar et al.[39]

defect rims. Retroaortic (anterosuperior) rim insufficiency is noted, but is not considered a contraindication to device placement. Multiplane two-dimensional echocardiography is used to estimate the largest defect diameter. TEE imaging is used to monitor placement of the delivery sheath across the defect, and to evaluate the balloon sizing of the defect, using gradual inflation of a flexible sizing balloon. The echocardiogram is used to determine the point of 'stop-flow' across the atrial septal defect. The image intensifier is used to measure the balloon diameter at the point of 'stop-flow,' and this is compared with the TEE measurement of the balloon diameter at this point. If the 'stop-flow' diameter exceeds the estimated largest defect diameter on TEE a careful re-evaluation is suggested, prior to device placement.[12,17,43–45] TEE is then used to monitor the deployment of the septal occluder, documenting the placement of the left disk within the left atrium, the stent within the atrial septum, and the right sided disk on the right side of the atrial septum. TEE is used to document complete occlusion of the defect, both prior to and following release of the device from the delivery cable. TEE is used to evaluate the presence of pericardial effusion, both prior to and

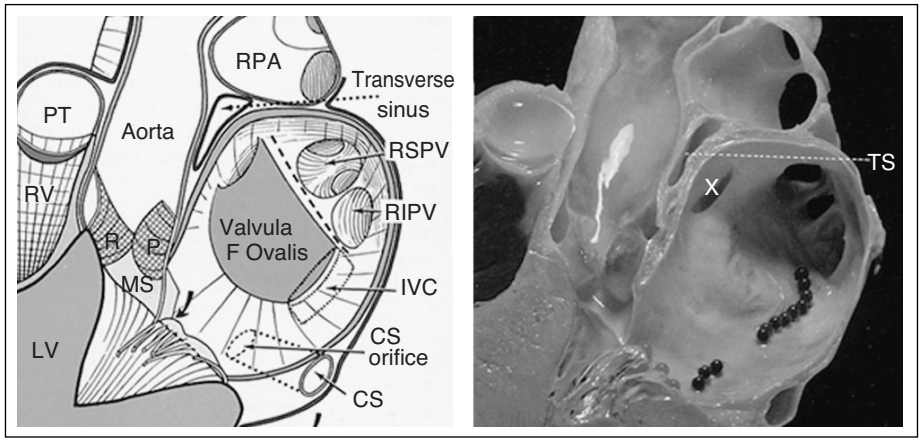

Figure 3.4
Transilluminated, waxed specimen, demonstrating left atrial aspect of the atrial septum, with three-dimensional rendering of same. Note the relationship between the foramen ovale (X) and the aortic root, the right superior pulmonary vein (RSPV), and the transverse sinus (TS).

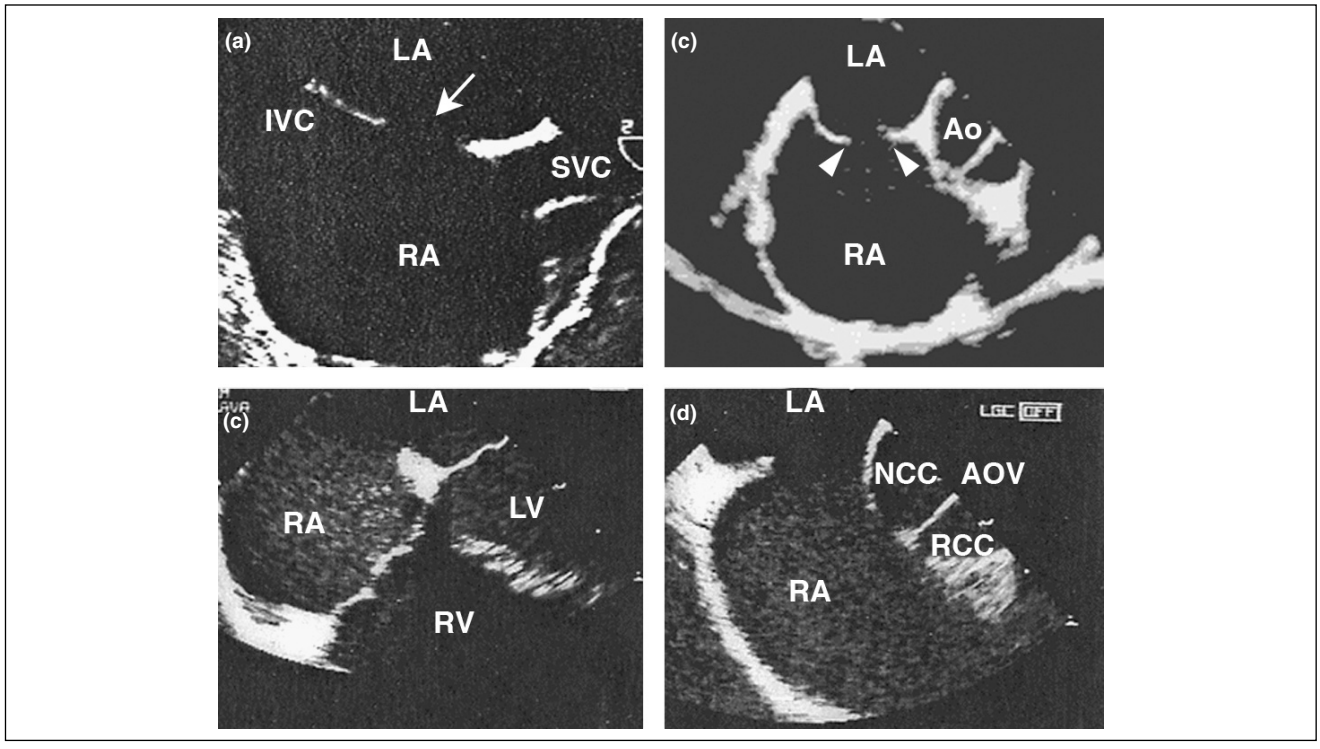

Figure 3.5
Four panels demonstrating transesophageal images of ostium secundum defects from differing vantage points. Upper left panel demonstrates centrally placed ostium secundum defect (arrow), with superior and inferior vena caval (SVC, IVC) entry points visualized. There is adequate rim at both locations. Upper right panel demonstrates atrial defect (between arrowheads). Note aortic root (Ao) in the right aspect of the figure, with adequate retroaortic rim. Lower left panel demonstrates adequate inferoanterior defect rim, near the atrioventricular valves. Lower right panel shows a large atrial defect, virtually abutting the non-coronary cusp (NCC) of the aortic valve, in a patient with a deficient (absent) retroaortic (anterosuperior) rim. (Reproduced from Du et al[17].)

following the occlusion procedure, with close follow-up recommended when a new or enlarging pericardial effusion is identified. TEE is also used to determine that the atrial septal occluder is not interfering with flow from the right superior pulmonary vein, or with the normal function of the atrioventricular valves.

Summary

In summary, transesophageal imaging provides images that are both unique and complementary to the fluoroscopic and angiographic images obtained during diagnostic and interventional catheterization procedures. By providing

visualization of the soft tissue of the atrial septum, TEE affords the opportunity to assess the candidacy of specific defects for device closure. Visualization of defect rims and the relationship of the defect(s) to important surrounding structures is afforded by this technique, which adds to the safety and efficacy of device closure for atrial septal defects in the catheterization laboratory.

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4

Imaging during cardiac catheterization: intracardiac echocardiography (ICE) using the AcuNav® catheter

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Introduction – an overview of intravascular and intracardiac imaging

Ultrasonography, with a probe placed directly in the vascular system, has been in existence for over two decades. Initial probes, mounted on intravascular catheters/sheaths, produced radial or 360° axial imaging.[1,2] In addition, relatively high frequencies were used such that images demonstrated excellent resolution of the vessels in which the ultrasound catheters were placed (e.g. coronary arteries); however, other portions of the cardiac anatomy were not well seen.[3–6] With the development of lower frequency transducers, greater depth penetration was possible allowing improved imaging of other parts of the cardiac anatomy;[7] hence the term 'intracardiac (ICE)' rather than 'intravascular (IVUS)' echocardiography to denote the location of the catheter. Axial or radial intracardiac imaging has been used to determine chamber and valve sizes, thicknesses, and function.[8–13] In addition, this type of imaging was also used for guidance of cardiac interventions such as endomyocardial biopsy,[14] trans-septal puncture,[15] and electrophysiologic studies.[16] During the latter, ICE has been used to guide the placement of electrophysiologic pacing catheters and trans-septal puncture, as well as to evaluate lesion size, anatomy, and post-procedure complications.[17–19] Since initial intracardiac imaging used an axial plane only, only portions of the two-dimensional (2D) anatomy were visualized at a time, and only a poor mental sense of the underlying 3D anatomy was possible. In addition, initial ICE catheters lacked pulse Doppler capabilities. Linear array transducers[20] and steerable catheters[20,21] were developed to enhance 2D visualization. Over the last 5 years, phased-array intracardiac transducers[22–24] have been introduced and essentially replaced other intracardiac imaging catheters. These ultrasound catheters have lower frequency as well as Doppler imaging capability. They have been used for guidance in numerous invasive cardiac procedures and interventions, including electrophysiologic studies,[25–28] balloon atrial septostomy,[29] gene insertion,[30] and closure of atrial level defects.[31–34] ICE has been shown to have imaging comparable to prior imaging modalities used during cardiac interventions,[34,35] and is perhaps a superior imaging method.[36–38] The cost of ICE had been deemed prohibitive, but investigators have shown that the costs may be equal to or less than prior imaging modalities.[39]

Description of the ICE catheter

ICE is currently performed using the AcuNav® catheter (Acuson Corporation, A Siemens company). The original catheter has a 10.5 Fr (3.2 mm) shaft that requires an 11 Fr introducer. The transducer has a frequency which varies from 5.5 to 10 MHz and contains a 64-element phased array. The sector scan of this transducer is in a longitudinal (with respect to the catheter) plane and achieves a 90° sector image with a depth penetration of up to 12 cm. Furthermore, the catheter is steerable via a four-way tip articulation allowing maneuvering in four directions. The handle is equipped with a locking knob that allows the tip of the catheter to be fixed in a desired orientation (Figure 4.1).

In adult patients, the AcuNav catheter can be introduced in the same vein used for the device delivery. However, for patients weighing less than 35 kg (i.e. children), the contralateral femoral vein is used. However, a newer catheter which is 8 Fr in diameter is now available for use. The catheter has similar imaging capability and will require only an 8 Fr introducer.

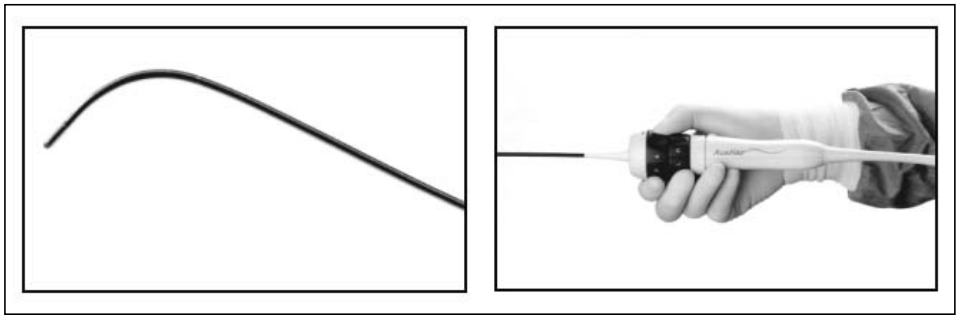

Figure 4.1
The AcuNav® catheter. Left, the tip of the catheter can be manipulated in four different directions. Right, the control handle has three knobs: one to move the tip in posterior/anterior directions, one to move the tip right/left, and the last knob is a locking one that will fix the tip in the desired orientation.

ICE imaging protocol during device placement

The use of ICE during atrial septal defect (ASD) and patent foramen ovale (PFO) closure using a phased-array transducer has been described.[31] At the start of the case, a complete evaluation of the defect(s) and surrounding anatomy is performed. The intensity of this interrogation will in part depend on the adequacy of and completeness of imaging prior to the procedure. For patients with an ASD, the size of the defect via 2D imaging (with and without being stretched by a balloon) as well as the measurement of surrounding rims is obtained. Contrast injection via agitated saline microbubbles is performed for patients with a PFO.

Step-wise protocol for ICE imaging to guide ASD or PFO closure

1. ICE imaging is initiated after advancing (under fluoroscopic guidance) the catheter to the mid-right atrium, also referred to as the 'neutral view' or 'home view'. The ICE catheter is parallel to the spine with the transducer portion facing the tricuspid valve. This is shown in Figure 4.2(a). Diagrams depicting catheter position via fluoroscopy (in the anteroposterior (AP) view) as well as the corresponding imaging planes and the image obtained by ICE are shown. In this view, the tricuspid valve, right ventricular inflow and outflow, and a long axis of the pulmonary valve are seen. The aortic valve can also be seen in a transverse (short-axis) view. The anterior part of the septum can be seen in this view.
2. The ICE catheter is flexed posteriorly using the knob so that the transducer faces the interatrial septum. Fluoroscopy showing the position of the catheter, as well as a corresponding anatomic diagram, is shown in Figure 4.2(b). The ICE image obtained shows the interatrial septum as well as the coronary sinus and pulmonary veins, depending on the exact location of the transducer. This can be referred to as the 'septal view'. One can obtain further views by locking the tip in this position and rotating the entire handle or by fine adjustments of the posterior/anterior or right/left knobs.
3. The ICE catheter itself is then advanced in a cephalad direction toward the superior vena cava (SVC). This can be referred to as the SVC or 'long-axis view'. A fluoroscopic image showing the position of the catheter as well as a corresponding anatomic diagram is shown in Figure 4.2(c). The ICE image obtained is also shown. In this plane, the transducer faces the interatrial septum and the SVC can be seen as it relates to the right atrium. The interatrial septum is shown in a superior/inferior plane and corresponds to the transesophageal echocardiography (TEE) long-axis view. Greater portions of the SVC can be seen by continued advancement of the ICE catheter in this flexed position toward the SVC. Greater portions of the inferior septum can be similarly imaged by withdrawing the ICE catheter toward the inferior vena cava in the flexed position. A defect of the interatrial septum can be well profiled, and the superior and inferior rims as well as the diameter of the defect can be measured. In this view, both the right and left pulmonary veins may also be imaged, depending on the exact angle of the imaging plane.
4. The catheter (in its locked position) is then rotated clockwise until it sits in a position with the transducer near the tricuspid valve annulus, and inferior to the aorta. A fluoroscopic image showing the catheter position and a corresponding anatomic diagram is shown in Figure 4.2(d). The ICE image obtained is also shown. In this view, the aortic valve can be seen in the short axis as well as the interatrial septum. This corresponds to the basal short-axis view obtained with TEE and is known as the 'short-axis view'. However, the right atrium is in the near field and the left atrium is in the far field, which is opposite to what is seen with TEE.

Prior to the actual device deployment procedure, the above views are obtained in order to image the ASD or PFO. Additional views can be obtained by advancing the catheter through the ASD or PFO into the left atrium (see below). From this position, an equivalent of the transthoracic four-chamber view can be obtained with views of the mitral valve, left ventricle (LV), and right ventricle

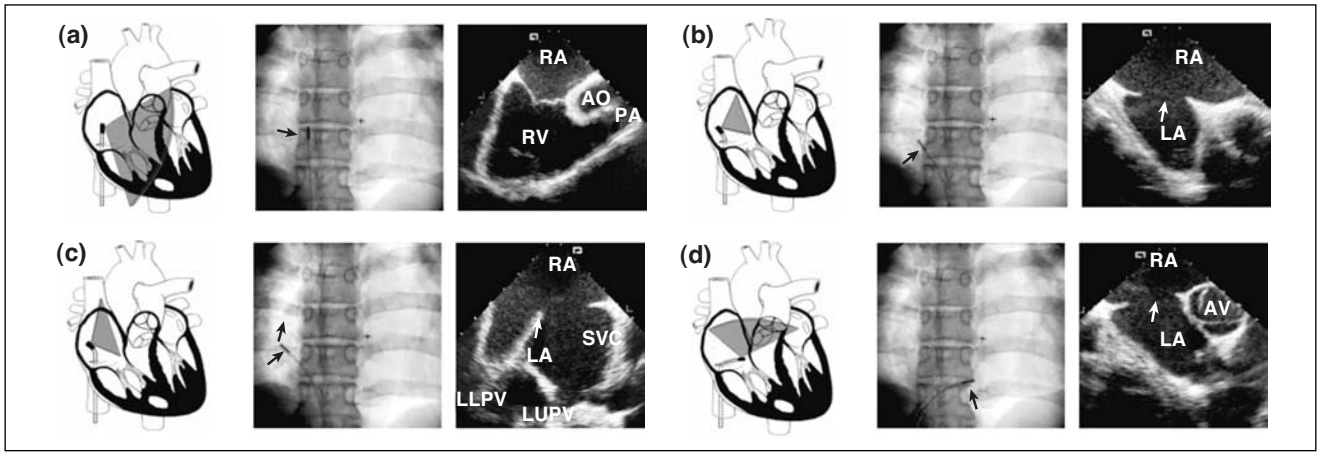

Figure 4.2
(a) Images in the home view. Left, sketch representing the heart with the position of the intracardiac catheter inside the heart with the ultrasonic array box in the neutral 'home view' position. The shaded area represents structures seen in this view. Middle, a cine fluoroscopy image showing the position of the ICE catheter (arrow) in the mid-right atrium with the transducer facing the tricuspid valve and parallel to the spine. Right, an actual intracardiac echocardiographic image with the ultrasonic box in the neutral home view position. The tricuspid valve, right ventricle out, and inflow are well seen in this position. The aortic valve and pulmonic valve can also be seen. AO, aortic valve; RA, right atrium; PA, pulmonary artery; RV, right ventricle. (b) Images in the septal view. Left, sketch representing the heart with the position of the intracardiac catheter inside the heart with the ultrasonic array box in the posterior flexed position looking at the atrial septum 'septal view'. The shaded area represents structures seen in this view. Middle, a cine fluoroscopy image showing the position of the ICE catheter (arrow) in the right atrium with the transducer flexed posterior looking at the septum. Right, an actual intracardiac echocardiographic image with the ultrasonic box in the septal view. The atrial septal defect is well seen (arrow), as are the left and right atria. (c) Images in the long-axis 'caval view'. Left, sketch representing the heart with the position of the intracardiac catheter inside the heart with the ultrasonic array box in the posterior flexed position with a cephalad advancement looking at the atrial septum and the superior vena cava 'caval view'. The shaded area represents structures seen in this view. Middle, a cine fluoroscopy image showing the position of the ICE catheter (black arrow) in the right atrium with the transducer flexed posterior looking at the superior vena cava (white arrow). Right, an actual intracardiac echocardiographic image with the ultrasonic box in the caval view. The atrial septal defect (arrow), the left and right atria, the left pulmonary veins, and the superior vena cava are all well seen. SVC, superior vena cava; LLPV, left lower pulmonary vein; LUPV, left upper pulmonary vein. (d) Images in the 'short-axis view'. Left, sketch representing the heart with the position of the intracardiac catheter inside the heart with the ultrasonic array box in the flexed position and the entire handle rotated clockwise until the imaging transducer is above the tricuspid valve looking at the aorta from below. In this position, fine rotation of the knobs can demonstrate different parts of the atrial septum. The shaded area represents structures seen in this view. Middle, a cine fluoroscopy image showing the position of the ICE catheter (black arrow) in the right atrium with the transducer above the tricuspid valve. Right, an actual intracardiac echocardiographic image with the ultrasonic box in the short-axis view. The atrial septal defect (arrow), the left and right atria, and the aortic valve are all well seen. This view is similar to a TEE short-axis view with the left atrium in the far field (opposite to the TEE).

(RV). The catheter can be further manipulated to view the left atrial appendage (LAA), which may be helpful in procedures to occlude the LAA. The catheter is then withdrawn back to the right atrium. During exchange wire and delivery sheath positioning, the long-axis view is felt to best delineate intracardiac relations. Device deployment is monitored in the long-axis view as well to demonstrate the relation of the disks to the interatrial septum. Figure 4.3(a)–(o) demonstrates the case of a patient with a large secundum ASD who underwent device closure. This figure demonstrates all the steps involved in device closure using the Amplatzer Septal Occluder. Color Doppler imaging as well as contrast echocardiography is used to assess for the presence or absence of any residual shunts.

In summary, the routine ASD or PFO closure procedure uses ICE to demonstrate catheter, guidewire, and sheath placement across the ASD or PFO. After placement of the sheath, ICE imaging is used to show the manner in which the occluder device is advanced within the sheath. It is then used to show deployment of the device as it is advanced out of the sheath: left disk opening, positioning of the left disk toward the interatrial septum, waist deployment, and right disk deployment as these in turn are advanced out of the catheter. Finally, release of the device is imaged.

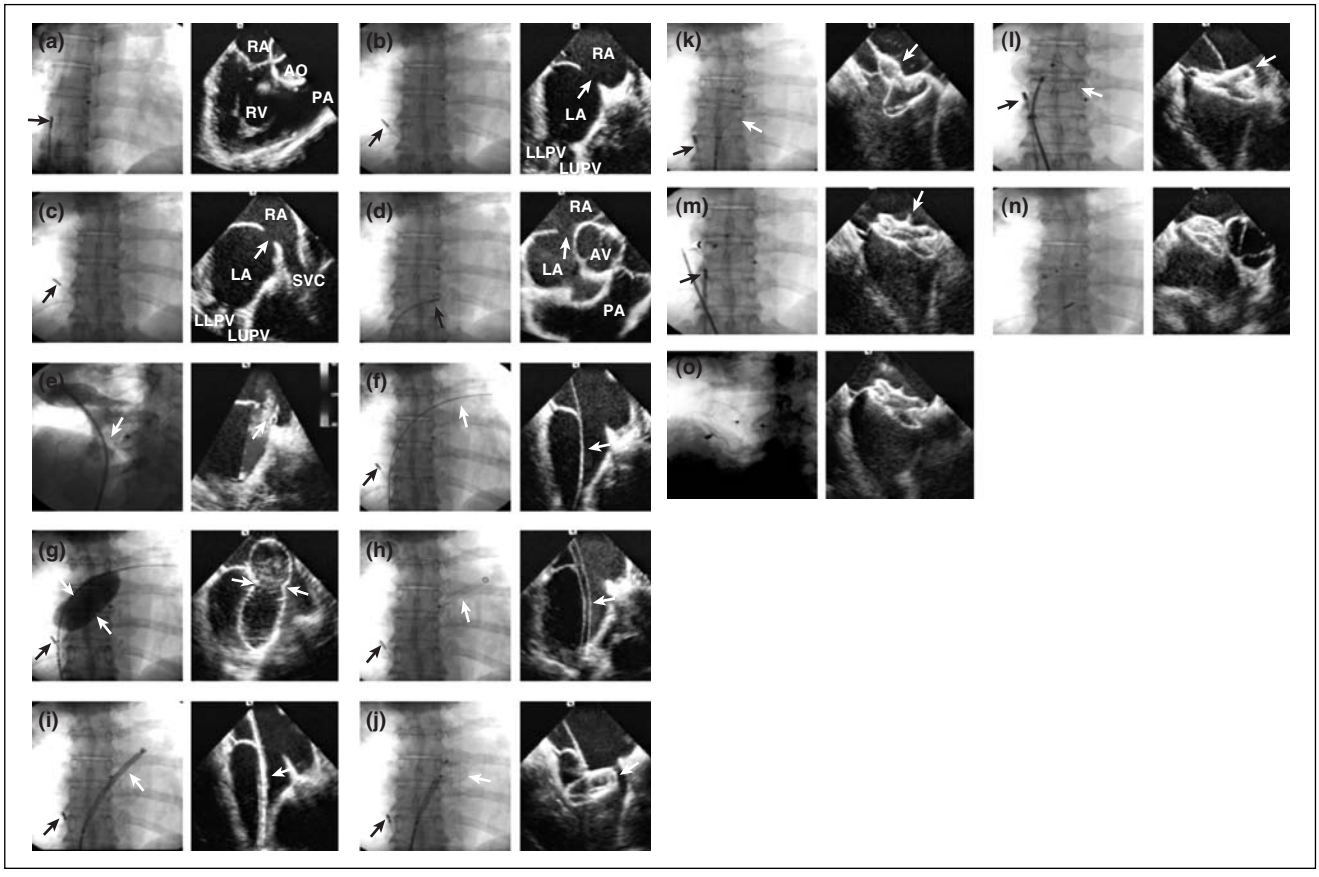

Figure 4.3
Cine fluoroscopic and ICE images in a 54-year-old female patient with a large secundum ASD who underwent closure using a 28 mm Amplatzer Septal Occluder. (a) Left, cine of the ICE catheter in the home view (arrow). Right, image obtained showing the tricuspid valve, right ventricle, aorta, and pulmonary artery. (b) Septal view images. Left, ICE transducer (arrow) facing the septum. Right, ICE image obtained demonstrating the defect (arrow), pulmonary veins and left and right atria. (c) Caval view images. Left, ICE transducer (arrow) facing the upper septum and looking at the superior vena cava. Right, ICE image obtained demonstrating the defect (arrow), SVC, pulmonary veins, and left and right atria. (d) Short-axis view images. Left, ICE transducer (arrow) above the tricuspid valve. Right, ICE image obtained demonstrating the defect (arrow), aortic valve, pulmonary artery, and left and right atria. (e) Left, angiogram in the right upper pulmonary vein demonstrating the defect (arrow). Right, ICE image with color in septal view demonstrating the defect and shunt (arrow). (f) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in the septal view position during passage of the exchange guidewire (white arrow) through the defect into the left upper pulmonary vein. Right, corresponding ICE image showing the guidewire (arrow) through the defect. (g) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in the septal view position during balloon sizing of the defect to obtain the stretched diameter (white arrows). Right, corresponding ICE image showing the indentations on the balloon (arrows). (h) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in the septal view position during passage of the delivery sheath (arrow) into the left atrium. Right, corresponding ICE image showing the delivery sheath (arrow) inside the left atrium. (i) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in the septal view position during passage of a 28-mm Amplatzer Septal Occluder within the sheath (arrow). Right, corresponding ICE image showing the device inside the sheath (arrow). (j) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in the septal view position during deployment of the left atrial disk (arrow) of a 28-mm Amplatzer Septal Occluder in the left atrium. Right, corresponding ICE image showing the left disk in the left atrium (arrow). (k) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in the septal view position during deployment of the connecting waist (arrow). Right, corresponding ICE image showing the connecting waist (arrow). (l) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in a modified septal short-axis view position during deployment of the right atrial disk (arrow). Right, corresponding ICE image showing the right atrial disk (arrow). (m) Left, cine fluoroscopy image demonstrating the ICE catheter (black arrow) in a modified septal short-axis view position after the device has been released from the cable (white arrow). Right, corresponding ICE image showing the device after it has been released (arrow). (n) Left, cine fluoroscopy image demonstrating the ICE catheter in a modified short-axis view position. Right, corresponding ICE image showing the aortic valve and both disks of the device. (o) Left, cine fluoroscopy image in the four-chamber view demonstrating the position of the device. Right, ICE image with color Doppler showing good device position and no residual shunt.

ICE imaging protocol for VSD closure

The use of ICE during VSD closure using a phased-array transducer has been described.[40] At the start of the case, a complete evaluation of the defect(s) and surrounding anatomy is performed. Similar to ASD or PFO closure, the intensity of this interrogation will in part depend on the adequacy of and completeness of imaging prior to the procedure.

Stepwise protocol using ICE to guide VSD

The ICE catheter is introduced in the same fashion for VSD closure as it is for transcatheter ASD or PFO closure described above. Under fluoroscopic guidance, the ICE catheter is advanced from the inferior vena cava (IVC) into the right atrium (RA). A complete ICE study then ensues.

1. ICE imaging is initiated in the RA with the 'home view' similar to ASD and PFO closure, as described above. The ICE catheter is advanced through the IVC and into the middle of the RA, with the tip of the catheter placed in a neutral position, and the orientation of the imaging plane toward the tricuspid valve, as shown in Figure 4.4(a). From this position, the RA, the right ventricle (RV) inflow, and the membranous/perimembranous portion of the interventricular septum (IVS) are seen. The defect within the IVS is noted and its relationship to the tricuspid valve is shown in Figure 4.4(a).
2. The short-axis view is obtained similar to that obtained during ASD and PFO closure. The catheter is flexed posteriorly and locked. The entire handle is rotated clockwise and advanced slightly just above the tricuspid valve until the short-axis view is achieved, with the transducer in an anterior–superior plane as shown in Figure 4.4(b). A fluoroscopic image of the catheter and the corresponding ICE image are shown. This view demonstrates the location and size of the defect, the aortic valve, and the pulmonic valve.
3. A four-chamber view is obtained by maneuvering the ICE catheter into the mid-RA with the tip positioned slightly anterior (close to the interatrial septum), and rotation such that the orientation of the imaging transducer faces the LV, as shown in Figure 4.4(c) with the accompanying fluoroscopic and ICE images. In this view, the entire left atrium and ventricle can be seen, as well as part of the right atrium and ventricle. This view is important to show disk deployment and the position of the disk in relation to the IVS.

In the patients with an associated atrial communication (ASD or PFO), the ICE catheter can be advanced across the atrial defect from the RA into the left atrium (LA) under fluoroscopic guidance. This positioning of the ICE catheter allows the following additional views:

1. The longitudinal view is obtained with the catheter in the left atrium with slight advancement of the ICE catheter in a flexed position toward the mitral valve and a 90º anterior flexion of the tip. This provides an imaging plane toward the LV long axis as depicted in the anatomic diagram in Figure 4.5(a). The corresponding fluoroscopic and ICE images are also shown. The ICE image demonstrates the LA, mitral valve, LV inflow and outflow, the long axis of the aortic valve, as well as the defect and the rim in the subaortic valve region.
2. The basal subaortic short-axis view is obtained with the ICE catheter advanced into the middle of the LA with a 45º anterior flexion of the transducer, as shown in Figure 4.5(b). This figure also shows the corresponding fluoroscopic and ICE images. The ICE image demonstrates the RA, RV inflow and outflow, and the short axis of the subaortic valve region and the defect.
3. The four- and five-chamber views are obtained by advancing the ICE catheter to the middle of the LA with a 90º anterior flexion of the tip. This provides an imaging plane facing the apex of the heart as seen in Figure 4.5(c), with the corresponding fluoroscopic and ICE images. The ICE images demonstrate a four- or five-chamber view of the cardiac structures. The latter views clearly demonstrate the subaortic rim of the defect, the relation of the defect to the aortic valve, and the relation of the device to the aortic valve.

In summary, the VSD closure procedure uses ICE to show the pertinent anatomy of the VSD including the defect and its rims, and the relation of the defect to the aortic valve. It is then used to demonstrate catheter, guidewire, and sheath placement across the VSD. After placement of the sheath, ICE imaging is used to demonstrate the manner in which the occluder device is advanced within the sheath. It is then used to show deployment of the device as it is advanced out of the sheath: left disk opening, positioning of the left disk toward the interventricular septum, waist deployment, and right disk deployment as these in turn are advanced out of the catheter. The release of the device is imaged, followed by imaging of the relation of the device to surrounding structures, especially the aortic valve and tricuspid valves.

ICE imaging for other cardiac interventional procedures

The use of ICE for other cardiac interventions precedes its use for the closure of septal defects. Its use has been well described to help guide transeptal puncture,[41] for the