
Cardiac Catheterization in Congenital Heart Disease: Pediatric and Adult

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Preface

This text is intended for all individuals who are involved with the cardiac catheterizations of infants, children and older patients with congenital heart disease. The catheterization of a patient with congenital heart disease requires a thorough background knowledge of the normal and abnormal cardiac anatomy, a skill at catheter manipulation and an additional “feel” for that anatomy. The skill necessary for maneuvering a catheter is acquired with experience but the use of these skills also involves some individual intuition. Hopefully, this text will help in attaining the acquired skills, while the experience in using these techniques will provide the “feel”!

The material in this text emphasizes the *minute details and fundamentals* of catheter manipulations and procedures, which are required for the correct and efficient acquisition of the data necessary for meaningful calculations during diagnostic catheterizations. As always has been the case, diagnostic catheterization still only is as good as the accuracy of the data and the interpretation of the data from that catheterization. This text also provides the details of

techniques necessary for effectively and safely accomplishing most of the complex therapeutic catheterization procedures that are available currently.

The information contained in this text does have a definite bias as it represents the accumulation of knowledge, techniques and procedures learned, utilized and/or developed by the author during the continued learning, practice and teaching of cardiac catheterization procedures during the past, extremely exciting, four decades in the field. Although much of the past 35 years of this experience has been at Baylor College of Medicine/Texas Children’s Hospital, the opinions that are expressed are not necessarily those of the institutions.

The “free hand” drawings in this book were provided by Jeremy Rountree. Jeremy is a senior art student in college and a long-time patient of mine. All of the “computer generated” drawings as well as a few modifications of some of Jeremy’s drawings were the responsibility of the author.

Charles E. Mullins, MD

Dedication

This book is dedicated to Arlene, who has stuck by me and been tolerant of me for five decades in spite of my “competing love” of medicine and the cardiac catheterization laboratory. She has been remarkably patient and supportive while awaiting the conclusion of this particular project.

And to Dr Weldon Walker, my mentor in cardiology at Walter Reed General Hospital, who not only taught me cardiology and the techniques and the art of cardiac

catheterization, but instilled in me the concepts of perfection and “never taking anything for granted”.

And to Dr Dan G. McNamara, my close friend, my associate, my chief and my continuing mentor for the first twenty-five years at Texas Children’s Hospital. Dan not only tolerated my activities in the catheterization laboratory, but supported and encouraged me no matter how outlandish my projects may have seemed.

Introduction

There is no “standardized” cardiac catheterization procedure for any pediatric and/or congenital heart patient and/or lesion, any more than any of the complex lesions in these patients are standardized. For the catheterizing physician, each cardiac catheterization procedure is an individualized, totally new experience—some far more so than others—on each new patient and even for repeat catheterizations on the same patient. As a consequence *every* catheterization procedure is a *learning experience* for the catheterizing physician. As procedures are performed repeatedly, the operator becomes more comfortable with the technique and with the limits of the particular procedure. Often this results in “extending” the limits of old procedures and when modified logically and methodically, to the development of new procedures. Almost all of the diagnostic and therapeutic procedures utilized in the catheterization laboratory have developed and/or were perfected through such an evolution.

The procedures and techniques that are described in detail in this text, may not be the “quickest” way to perform a procedure, but rather, the techniques emphasize *reliability* and *safety*, often at the expense of “speed”. During the performance of any catheterization procedure, when some specific step and/or part of a safe and established procedure is abbreviated or bypassed in order to “save time”, the “short cut” is more likely to result in errors in the data that are acquired, to increased risks for the patient and/or even to result in the total failure of the procedure.

Much of this information will be mundane and of little use to the pediatric cardiologist who is experienced in therapeutic catheterization procedures, however, the goal of this text is to cover the *minute details* of most available cardiac catheterization techniques and procedures. With the avalanche of new devices, procedures and techniques that are being developed, many procedures and devices used in the cardiac catheterization laboratory have come and gone, and will continue to come and go. All of the devices and procedures that remain in use have been

modified and/or improved over the years. Undoubtedly, before this text even is published, some of the information will be obsolete. On the other hand, the basic techniques of catheter manipulation and therapeutic procedures are sound, very well tested and should be valid as long as cardiac catheterizations are being performed. Hopefully there will be some information of value for physicians performing cardiac catheterizations at all skill levels.

The demise of diagnostic cardiac catheterization was predicted three decades ago with the introduction of echocardiography, magnetic resonance imaging (MRI) and computed tomography (CT) imaging. With the subsequent evolution of these non-invasive diagnostic modalities over the past three decades all of these modalities individually have been designated to replace diagnostic cardiac catheterization. On the contrary, the need for very detailed and accurate diagnostic cardiac catheterizations in pediatric and congenital heart patients actually has increased. The extremely complex and sophisticated surgery being undertaken for the more and more complex and very bizarre congenital heart defects demands accurate diagnoses that are even more precise.

Although many lesions are diagnosed and referred directly to surgery on the basis of the non-invasive studies, there are innumerable occasions, particularly in the very complex lesions, where more specific details about the anatomy and/or hemodynamics are necessary in order for the surgeons to be able to embark on the more exotic repairs. In 2005, cardiac catheterization still remains the “final court” for the definitive anatomic and hemodynamic diagnoses for most of the very complex lesions where the very precise and very complete information about *all* of the anatomy and physiology still is obtainable only from a thorough, accurate cardiac catheterization. At the same time, the more information from the clinical data and the non-invasive studies that is available prior to the catheterization procedure, the more organized and expedient is the catheterization and the more valid are the data obtained from the catheterization.

In addition to the essential diagnostic information that still only can be acquired from a precise and detailed cardiac catheterization, definitive *therapy in the catheterization laboratory* has become the major indication for cardiac catheterization for many of the lesions in pediatric and congenital heart patients. The numerous therapeutic procedures performed in the cardiac catheterization laboratory have generated an even more essential and often, more challenging, need for extremely precise and purposeful maneuvers with cardiac catheters. The catheters for the delivery of balloons and/or devices must be positioned in very precise locations, not just into the general vicinity of the lesion.

In order to proceed with the appropriate and expedient therapeutic catheter intervention, the accurate diagnosis must be acquired, a decision must be made on the basis of that information during the procedure and then, immediately, the information is acted upon therapeutically. In most cases, the therapeutic procedure is performed during the same catheterization procedure without a decision by "conference". The therapeutic catheterization procedures have resulted in the development of new equipment along with entirely new procedures and techniques, which catheterizing physicians not only must become familiar with, but also must be experts in performing.

The therapeutic catheterization procedures also have

stimulated a new collaboration between the interventional cardiologist and the congenital heart surgeon. In progressive institutions, the catheterizing interventional cardiologist plans his diagnostic and therapeutic catheterization interventions based on the stage of surgical repair, which is to be performed subsequently in the operating room. The surgeon also can plan his procedure based on the knowledge that a subsequent therapeutic intervention to "complete the repair" may be performed more expeditiously in the catheterization laboratory. More and more frequently, therapeutic catheter interventions are performed in conjunction with the surgeon *in the operating room*. Therapeutic catheterizations that are performed in the operating room overcome some access problems for the catheter intervention and at the same time allow better myocardial protection with shorter, or even *no* cardiopulmonary bypass and/or arrest times during the operative procedure.

This text is intended to provide detailed instructions for most of the therapeutic catheterization procedures presently in use for congenital heart defects. Although many of these specific catheter maneuvers are useful during intracardiac electrophysiologic procedures, the specific electrophysiologic diagnostic and therapeutic interventions represent an entirely separate specialty and are not discussed in this text.

1

Organization of a pediatric/congenital cardiac catheterization laboratory

Introduction

The recommended equipment and the arrangement and organization of the space and equipment for the pediatric/congenital cardiac catheterization laboratories which are discussed in this chapter are a culmination of my own experience in cardiac catheterization laboratories over the past 40+ years. During that time I have had the privilege/opportunity of performing catheterizations in some 180 different catheterization laboratories in 120 different institutions throughout the US and much of the rest of the world. During that time I also had the experience of directing several catheterization laboratories for more than 25 years and of having a significant role in, and part of the responsibility for, building 14 different cardiac catheterization laboratories in several different hospitals over those years. The equipment, space and personnel requirements described in this chapter meet or exceed all published standards for pediatric/congenital cardiac catheterization laboratories^{1,2}. The cardiac catheterization rooms/suite described in this chapter are in operation at Texas Children's Hospital.

The total space requirement for a twenty-first century pediatric and congenital cardiac catheterization room (laboratory) and the accompanying support area or "suite" is significantly greater than for the catheterization laboratory of even one decade ago. The increased requirement for space is a consequence of the physical dimensions of the modern, biplane X-ray equipment, which is capable of compound angulation of both X-ray tubes, the sophisticated ancillary electronic equipment which is required and the increased complexity of the procedures which are now performed in these laboratories. Many of the therapeutic catheterization procedures require additional, large pieces of ancillary equipment (anesthesia machines, transesophageal and intracardiac echo, equipment for partial or total cardiac support, etc.), which not only must be in the catheterization laboratory,

but often must be positioned immediately adjacent to the catheterization table. Significant *additional* space also is required to "park" each of these pieces of equipment in the immediate vicinity of the laboratory, if not actually within the catheterization room, when they are not actually in use.

With the longer, more complex procedures and particularly with the frequent use of implants in the catheterization laboratory the cardiac catheterization *room* should be considered a "sterile" environment similar to an operating room. The catheterization room should operate with the doors to adjacent areas (except the control room) closed and it should have a separate, filtered air input which maintains a "positive pressure" circulation within it³. At the same time, because of frequent equipment maintenance and other outside support, the entire catheterization *area* or *suite* adjacent to, but outside of the actual catheterization room, is considered a "clean", rather than sterile, area.

The exact location of the catheterization area in relation to other hospital facilities often is dependent upon overall space availability and requires considerable pre-planning. Optimally, pediatric/congenital cardiac catheterization laboratories are located immediately adjacent to, and have easy access to the pediatric/congenital cardiac operating rooms and cardiac intensive care areas. Although the need for surgical intervention during a cardiac catheterization is still very rare, when surgical support is needed, it is needed immediately. "Open chest", operative intervention is preferably performed in the operating room, not in the catheterization room. Having the surgical suite immediately adjacent to the catheterization laboratory and accessed through a sterile corridor allows a patient to be transported very rapidly and expediently from the catheterization laboratory to an operating room even when the patient is on external support or his chest is opened.

The requirements for, and the optimal arrangement of, the modern catheterization laboratory space are detailed in the following section.

The cardiac catheterization room itself

A current cardiac catheterization laboratory ideally should be at least 32 feet long by 24 feet wide. In addition to the large length and width requirements of the catheterization room, the ceiling height must be at least 14 feet in order to accommodate the suspension system of the X-ray tubes and intensifiers from any manufacturer. The *only* “fixed” equipment in the actual catheterization room should be the catheterization table and the suspension systems for the X-ray systems along with the X-ray and physiologic monitors, with no fixed cabinets and none of the X-ray generating equipment included within the actual catheterization room. The arrangement of the catheterization table in the room and the “connections” or “communications” to the room from adjacent areas depend upon the “real estate” which is available immediately adjacent to the catheterization room. The control room for the physiologic and X-ray systems must be adjacent to the catheterization room and have at least a doorway access to the laboratory. The control room can be positioned at the end or at the side of the catheterization room, but in either location the operators in the control room should have a clear view of the patient on the catheterization table. The storage for the majority of the expendable catheterization equipment should be immediately adjacent to the catheterization room with a readily accessible doorway. The catheterization room should have a one-and-a-half or even a double-width doorway for patient access. Even though the patient may arrive on a narrow hospital stretcher, there must be the capability of leaving the room easily with “attached” equipment and personnel adjacent to or alongside of the bed/stretcher during a resuscitation or emergency transfer to an operating room.

The scrub sink(s) for the catheterization laboratories should be located *outside* of the actual catheterization room in an adjacent “clean” corridor or room. It is essential that all personnel in the laboratory scrub before working in the room and that the physicians scrub between each case. At the same time, scrubbing, which is a relatively short task, is performed before the catheterization procedure. It has nothing to do with the procedure itself, it actually can have “dirty” fluids splashing away from the sink and, as a consequence, there is no justification, nor logic for having the scrub sink occupy valuable space within the catheterization room.

During the course of an interventional catheterization procedure the catheterization room can become very crowded with equipment and personnel. The location and arrangement of each piece of *fixed equipment* become critical for the most efficient and safe completion of the procedure.

X-ray equipment

The basic equipment in a catheterization laboratory for pediatric and congenital heart patients includes a biplane X-ray system with compound angulation capabilities, an extra-long catheterization table and dual (quadruple!) CRT or flat panel monitor screens. This basic equipment requires a very large “footprint” of floor space in the room for just the catheterization table and the suspension systems for the X-ray tubes/intensifiers. The catheterization table needs to be “extra long” or have a long extension at the foot end in order to prevent the contamination of the very long catheters, delivery systems and exchange length wires which are introduced and undergo multiple exchanges through the femoral vessels. The footprint of the catheterization table and the suspension system for the X-ray tubes/intensifiers should include enough width to allow unimpeded rotation of the X-ray tubes and support arms without bumping into or having to move other equipment. There must be significant space towards the head of the table to allow clear cephalad–caudal movement of the suspension system, space for physicians working from the head-end of the table, adequate space for relatively large anesthesia/respiratory equipment adjacent to the head *and* room to have a transesophageal echo console adjacent to the patient’s head. It is often necessary to have all of this space occupied at the same time! Additional floor space cephalad to, and away from the working areas is required to “park” the lateral X-ray suspension gantry a distance away from the head of the catheterization table in order to allow room for transferring the patient to and from the table.

The catheterization table

The spacial orientation of the catheterization table within the room helps to optimize the usable space. When the catheterization table is placed at an angle, somewhat diagonally across the room, this opens up a large area on one side of the table at the head of the table and an equally large area on the opposite side at the foot of the table. When the larger space at the head of the table is on the side of the access doorway for the patient, this allows a more convenient access to the table for a patient on a stretcher. As an added bonus, the extra space in this area opens up an area for a transesophageal echo machine working from the head of the table. The larger open area at the foot and on the opposite side of the table allows more working space for the physicians on that side of the table. A straight alignment of the table along the long axis in a slightly narrow room compromises the space on both sides of the table and for its entire length.

Work space for the physician/operators

In addition to the large space requirement for the X-ray equipment and the catheterization table, there must be liberal space adjacent to, and all around, the catheterization table/X-ray equipment to allow access to the table for other large pieces of support equipment. This space should allow unrestricted movement of the X-ray tubes and intensifiers as well as the free movement of the personnel within the laboratory around all of this equipment regardless of the positions of the X-ray tubes. The monitor screens are grouped together as a bank of monitors on a large ceiling mounted support, which is on tracks and is movable about the table. The operating physician must have a clear view of all of the monitors while looking *forward* (not over his shoulder or behind him), regardless of the site of catheter introduction into the patient. A very satisfactory arrangement is to have the bank of monitors mounted on a *long* swivel arm which, in turn, is on ceiling tracks aligned *across* the catheterization table at the foot of the table. With this configuration, the monitors can be moved directly over the foot of the table when vascular access is from either side of the neck or even the arm, and completely across the table when vascular access is totally from the left side of the patient. A *long* support arm on a swivel base for the bank of monitors allows sufficient movement of the monitors along either side of the table. With the multiple locations which are possible for the monitors, the operator can always be located across the table and facing the monitors with an unobstructed view of them without any body contortions or having to look round structures or behind him/herself.

The exact configuration of the catheterization table varies from laboratory to laboratory. Most catheterization tables are orientated for a right handed operator—i.e. with any extra space for the scrubbed physician(s) predominately on the right side of the patient's trunk. The person who operates the controls for the movement of the table and X-ray tubes and the person who operates the pressure/flush manifolds and the flush lines, all vary from laboratory to laboratory and affect how the catheterization table is configured. There must be adequate space for two, or possibly three, *scrubbed* operators on either side of the catheterization table particularly during complex therapeutic interventional procedures, when as many as four individuals may be scrubbed with several personnel on both sides of the table when the vascular access is from both sides. It also should be possible for at least two operators to work together from either side of the head and neck area while other operators are working from the femoral areas.

In the catheterization laboratories at Texas Children's Hospital, the table position/movements, the movement

of the C-arms suspending the X-ray tubes, the collimation of the X-ray tubes and the control and replay functions of the angiograms all are controlled by the catheterizing physician(s). As a consequence these controls are all maintained sterile with sterile covers/drapes and are positioned on the same (right) side of the patient as the operator, but nearer the foot of the table. In some laboratories these table/cine controls are operated by a separate technician or even a radiologist, in which case the controls are at the foot of the table or even physically away from the table on a separate stand.

In addition to the space for the table controls, an additional length of the table "real estate" along one side or the end of the catheterization table is required for the pressure transducers, pressure/flush manifolds and the flush/pressure lines. The manifold is a series of three or more, three-way stopcocks to which each transducer and the tubing to both the fluid reservoirs and to the patient are connected. In addition, the transducers are attached to electrical cables which run from the transducers to an electrical connection on the table and eventually to the physiologic recorders. When three or four transducers are used simultaneously during a case, the manifolds holding the transducers occupy a meter, or more along one edge of the table. Three-way stopcocks on the manifold allow "opening" the transducer to environmental pressure for balancing, as well as additional connections for the flush tubing to the transducers and separate tubing for flush/pressure lines to the patient from each transducer. In some catheterization laboratories where multichannel pressure recording is not used routinely, the manifold and even the transducers themselves are positioned on the catheterization "field" and operated by the catheterizing physician. Specifically arranged manifolds including the stopcocks, transducers and tubing are available commercially (Merit Medical Systems, Salt Lake City, UT). The exact positioning of the manifold on the surface or along the side of the table will depend upon which personnel operate the manifold during the case.

During the catheterization procedure, the manifold with the transducers ideally is fixed to the catheterization tabletop at a specific height on a stand which allows an initial adjustment in the height of the manifold to compensate for the "height" of the heart within the patient's chest above the tabletop. The exact level (height) for the pressure transducers varies and is determined for each individual patient according to the anterior-posterior (AP) diameter of the chest. The height for the transducer is the measured distance from the tabletop to the mid level of the posterior-anterior chest diameter, or the exact location of the heart is determined on the lateral fluoroscope. The height from the tabletop to the heart should be measured accurately with a ruler and then this exact measurement is

transferred to the transducer stand to determine the height of the transducers on the stand. When the transducers are attached to the table at the correct level on a stand, the transducers then move up and down *with the patient* when the table is raised or lowered and, in doing so, the reference height to the heart for *accurate* pressure measurements always remains exactly the same.

In the catheterization laboratories at Texas Children's Hospital, there are usually four transducers with as many as six to eight color-coded flush/pressure lines passing to the patient from pressure/flush manifolds. Each color-coded pressure line corresponds to a similar colored pressure curve which is displayed on the monitors. The entire manifold is operated by a designated nurse/technician who has no other *assigned* duty during the procedure. In this circumstance, the optimal position for the transducers is on the opposite side of the catheterization table as far as possible toward the foot of the table away from the operating physicians, but still within the sight of the catheterizing physician. Since the majority of catheter manipulations by the catheterizing physicians are performed through the femoral vessels and from the right side of the patient, regardless of whether the catheter is introduced from the right or left femoral vessels, the transducers optimally are fixed, semi-permanently, on the left (opposite) side of the table and as far as possible toward the foot of the table.

In some laboratories where one, or at most two transducers are used, the catheterizing physician operates the manifolds including the transducers, the stopcocks, and all of the fluid/pressure lines. In this circumstance, the manifold is fixed on the catheterizing physician's side of the table or actually laid on the patient's legs on the catheterization field. This arrangement is more suited when the catheterization laboratories are used predominantly for adult (coronary) catheterizations where less sophisticated hemodynamics usually are necessary.

Regardless of which vascular access site is used, there must be space located immediately behind the catheterizing cardiologist for at least one 30" × 60" work table to hold flush solutions, a container of contrast solution, needles, catheters, wires, instruments and other expendable equipment. The work table should have enough room around it to allow the "circulating" personnel and the operators to have access to and around the table without bumping into, or contaminating, it. *Two* large (30" × 60") work tables placed end to end behind the operators are optimal for interventional procedures where multiple long balloon catheters or very long delivery systems for device implants are utilized. The additional length of the two tables positioned end to end allows sufficient workspace for the preparation of the long balloon dilation catheters and device delivery catheters. The very long table prevents these long items from hanging over the

ends of the table and from being contaminated when they are stretched out lengthwise during their preparation or loading procedures.

Anesthesia space requirements

The anesthesiologist, along with the space for the anesthesia machine, requires access to the patient's head from either the right or left side of the patient. The anesthesia access is *cephalad* to the lateral X-ray support ("C") arm and must allow a convenient connection of the anesthesia machine/tubing to the patient's airway. Connections for oxygen, gas and suction lines usually come through the anesthesia machine from a separate ceiling- or wall-mounted console near the head of the catheterization table. It is essential that the oxygen, gas, suction console also is somewhat mobile and can be moved close to the patient's head for situations where general anesthesia and an anesthesia machine are not being used.

When general anesthesia is being used, the anesthesiologist controls the patient's airway while simultaneously operating the anesthesia machine. This requires a close proximity of the anesthesia machine to the head of the catheterization table. Anesthesiologists usually prefer the right side of the patient's head; however, when vascular access for the catheterization is available only from the right neck, it is preferable that the endotracheal tube connections to the anesthesia machine approach from the patient's left side. In rare circumstances, where vascular access and a complex procedure are to be from the right side of the patient's neck, it is desirable to have the anesthesia machine on the patient's left, as well.

A mobile, floor anesthesia machine provides more flexibility than a ceiling-mounted anesthesia machine when changes in the orientation of the room may be necessary to adjust for different access sites to the patient. At the same time, the floor anesthesia console does occupy considerable floor space.

This same need for sufficient room for access from a particular side of the head holds true for the patient who is on ventilator support without general anesthesia where the ventilator and the connecting tubing need a specific area and room for access. With or without a ventilator, a suction line/apparatus must always be adjacent to the patient's mouth and airway and must be immediately accessible.

Transesophageal echo

Although the transesophageal echo (TEE) console may not be "parked" permanently in the catheterization laboratory, the increasing frequency of use of TEE during congenital cardiac catheterizations has created an additional semi-permanent space requirement very close to the head

of the catheterization table. The connecting cable between the TEE probe and the echo console is relatively short, and the person manipulating the TEE probe frequently operates the console while manipulating the probe. As a consequence, the large TEE console is positioned very close to the head of the table. It must be possible to have access to the patient with the TEE probe *and the TEE machine* from either right or left side of the *head* of the table. The location of the TEE depends upon whether vascular access for the catheterization is from either the arm or neck and, in addition, on which side of the head the anesthesia access is located. The current TEE consoles also have a large footprint and necessitate a large amount of space cephalad to the head of the catheterization table, regardless of which vascular access to the patient is used.

The TEE machine is usually operated with the echo console positioned cephalad to the support arm for the lateral X-ray tube and intensifier and to the left of the patient's head. This places the echo console with its monitor and the operator cephalad to (and behind) the lateral image intensifier and out of the view of the catheterizing physicians. An additional mobile "slave" monitor away from the TEE machine will then be necessary in order for the operating cardiologist to see the TEE image. The remote monitor can be positioned away from the TEE console and directly in front of the *catheterizing physicians*, in order to allow the TEE image to be visualized continuously, no matter where the catheterizing physicians are positioned around the table relative to the TEE console. Ideally the slave TEE monitor is mounted with the other ceiling suspended (X-ray and physiologic) monitors. Another alternative is to have the slave monitor of the TEE mounted on a mobile floor cart, which can easily be moved to any open, viewable position around the table. Some X-ray systems allow a "picture in picture" positioning of the TEE image within the image of one of the X-ray monitors. This is not as satisfactory as may be perceived. If it is large enough to be usable the superimposed TEE image occupies approximately one-fourth of the X-ray image and always extends into, and compromises, the critical, *central area* of the X-ray image.

Whenever either X-ray tube is in an LAO-cranial position, the TEE console and the TEE operator physically compete with the location of the image intensifier. This requires good communication and, usually, some displacement of the TEE operator and the console when the X-ray tube/intensifier are rotated into, and remain in that position.

Adjunctive equipment required within the catheterization room

There is a considerable amount of additional, essential, but at the same time, usually mobile equipment in the

modern catheterization laboratory. This equipment, although mobile, remains in the catheterization room and takes up a finite, and often a significant amount of additional floor space there. This equipment includes the emergency medication/defibrillator cart, often a separate medication cart, the apparatus for blood oxygen saturation determinations, a patient-warming system, a cardiac output computer, and space for the mobile storage of very frequently used, consumable supplies. In some laboratories the angiographic injector, radiographic protective equipment, suction equipment and adjustable "operating field" lights are on floor-mounted, mobile stands, in which case they require additional floor space.

Emergency cart/defibrillator

Each cardiac catheterization room must have a mobile cardiac defibrillator and an "emergency cart" containing medications and resuscitative equipment. The defibrillator should have a rechargeable battery source of power in addition to a fixed source of (wall) electrical power. Often the emergency cart and defibrillator are combined into one mobile cart. The emergency cart contains items to establish an oral or nasal airway, equipment for endotracheal intubation, equipment to start intravenous or intra-arterial lines, suction catheters and the accessories for the defibrillator. Whenever a patient is in the room, the items on the emergency cart and the defibrillator must be available immediately and conveniently to the personnel in the room and to the patient. This, however, does not require that the emergency cart and defibrillator always be *immediately* adjacent the patient. However, the supplies on the emergency cart are organized in such a way that the location of each item on the cart is known instinctively and each item is available immediately to *all personnel* in the room. The defibrillator is turned on with the appropriate paddles for the patient attached to it and the paste for the paddles readily available. The correct voltage according to the size of the patient is set and the defibrillator is placed in a location from which there is immediate and unobstructed access to the patient during the procedure.

Medication tray/cabinet

In addition to the emergency and defibrillator cart(s), each catheterization room has a separate, readily accessible, medication tray or cart. The medication cart contains all of the emergency drugs, sedatives, and other medications used both in emergencies and more routinely in the cardiac catheterization laboratory as well as a variety of intravenous fluids. The details of the medications which are maintained in the medication cart are discussed in Chapter 2. This medication tray is located in close proximity to the manifold containing the transducers

and flush lines. When a nurse is operating the manifold, this nurse has immediate access to the medication cart and usually is responsible for administering medications from the cart.

Operating lights for the catheterization table

Movable or widely adjustable, focused lights over the operating field are essential in the catheterization laboratory. Free-standing floor lights, mounted on a mobile stand and with a long neck that extends over the catheterization table, were the standard for years and are still used in some institutions. These floor lights take up additional floor space immediately adjacent to the catheterization table, they often do not permit the light source to shine from the correct direction on the specific field, creating shadows rather than light over the working areas, and they are a constant potential for contamination of the sterile field. Ceiling-mounted operating room lights on long movable arms are the standard in most catheterization laboratories at the present time. Ceiling-mounted lights conserve floor space and allow the light to be directed more appropriately, but, when there are other ceiling-mounted accessories (angiographic contrast injectors and radiation protection screens), the ceiling-mounted lights add to the congestion in the area immediately above the catheterization table due to the multiple suspension arms. This congestion of the arms creates a problem in the optimal use of the other accessories.

The ideal lights for the catheterization laboratory are a set or group of recessed, high-intensity, focused, ceiling lights, which can be directed toward a specific spot on the catheterization table with a remote apparatus. The lights are adjusted by a small hand-held strobe light or "light wand", which is positioned immediately over the catheter introduction site. The strobe light positioned over the puncture site, in turn, directs each individual ceiling light to that specific spot on the catheterization table. With one, or several, of the lights mounted in the ceiling cephalad to the image intensifier (and the lateral tube X-ray suspension arm) and with the remainder of the lights mounted caudal to the image intensifier, excellent lighting is available to any area of the head, neck or arms as well as to the inguinal areas. These recessed lights do not interfere with other ceiling-mounted equipment and take up "no real estate", but do represent a very expensive initial investment.

Blood oxygen saturation analyzer

The oximeter apparatus for the analysis of blood samples for the immediate determination of oxygen saturations is situated in the catheterization room and in very close proximity to the catheterization table. Most oxygen

analyzers are located on a very small, mobile table or cart. The physician should be able to hand the syringe with the blood specimens for analysis directly to the technician/nurse for insertion into the analyzer and, at the same time, the technician should not have to take more than one or two steps between receiving the sample and inserting it into the analyzer. The results from most oxygen analyzers are displayed digitally on a very small screen on the analyzer. A read-out of the saturation results also should be clearly visible to the operator immediately, conveniently and on a large display in the catheterization laboratory. A large, immediately available display of the digital read-out of the oxygen saturation, the time of the sample and the location of the sample can be accomplished with some "hard wiring" from an A-Vox™ Oxygen Analyzer (A-VOX Systems, Inc., San Antonio, TX) to a "slave" computer with a large CRT or flat panel display, which utilizes special computer software which is now available from Scientific Software Solutions (Scientific Software Solutions, Inc., Charlottesville, VA). This provides a large, timed, instantaneous display of each oxygen saturation and its location as it is analyzed. The developed table of saturations, their time and location can be printed and used to verify the data that have been verbally transmitted to the computerized catheterization record.

Ideally, these same data could also be transmitted directly from the oxygen analyzer to the electronic record on the catheterization laboratory computer and be logged into the timed computer record without any verbal (shouted!), hand-written or manually typed transmission of the information. Unfortunately the small pediatric/congenital market has not been enough of an economic stimulus for any of the large manufacturers of physiologic equipment for the catheterization laboratory for them to provide the communication necessary to incorporate this already available, digital information into their physiologic monitoring/recording equipment.

Patient-warming equipment

Equipment for warming the patient is mandatory. Most cardiac catheterization laboratories operate in a very "cool" ambient environment. When the drapes on the patient become wet and room temperature (cold) flush solutions are continually running into the patient, most patients require supplemental support of their body temperature. The most effective means of maintaining the body temperature of the patient is to increase the environmental temperature of the catheterization room. For infants or debilitated patients, this requires an environmental temperature of up to 80° Fahrenheit. Such a high temperature is uncomfortable for most personnel within the room, but at the same time is absolutely necessary for

very small or debilitated patients regardless of the use of other supplemental warming systems. High environmental temperatures also interfere with the cooling of any X-ray generating equipment which happens to be positioned within the room and provide another strong argument for a separate equipment bay for this machinery.

There are several separate patient-warming systems commercially available for the catheterization laboratory. Separate, supplemental warming systems for the patient are attached directly to the table or the warming component is actually positioned on the catheterization table. The Bear Hugger™ hot-air warmers currently appear to be the most suitable system for cardiac catheterization procedures and they require a relatively fixed amount of floor space immediately adjacent to the catheterization table. The heating mechanism with its blower is usually positioned at the foot of the catheterization table. A connecting tube from the blower attaches to a very long U-shaped, sterile and disposable “paper tube”, the arms of which run, unobtrusively, under the sterile drape and along each side of the length of the patient. The warmed air is blown through these tubes around the patient under the drapes. The tubes do not interfere with access to the patient nor do they show up on fluoroscopy or angiograms.

Several other patient-warming systems are available which take up less fixed space around the table, but in general, are less satisfactory for use in the catheterization laboratory. The K-Pad™ heating system utilizes a plastic pad through which warm water is circulated. The pad, which is positioned under the trunk of the patient, is attached by tubing to a small heater/pump, which is placed on the catheterization table, under the drapes at the foot of the table. The K-Pad™ is not available nor suitable for patients of all sizes and the tubing within the pad is slightly radio opaque and, in turn, shows up on the fluoroscopy and angiographic images, particularly in smaller infants.

Another, even less satisfactory alternative for warming a patient is a floor-mounted “heating lamp”. These take up less space on the table and are very mobile, but they must be positioned immediately adjacent to, and over, the trunk of the patient, which always positions the lamp in the working area of either the operator or the fluoroscopy. Like the lights on a floor-mounted stand, the heating lamp extending over the trunk of the patient represents a constant potential for contamination of the sterile field. Of even greater concern is it that, in order to warm a patient through a very focused heat source from above, the heating lamp must generate a relatively high heat and must be positioned fairly close to the patient’s skin, the combination of which creates a real potential for actually burning the latter. The use of this type of lamp must be monitored very closely to prevent this occurrence.

Angiographic injector

The angiographic injector should be capable of being attached to the angiographic catheter from either side of the catheterization table, from the top or bottom end of the table and from any catheter introduction site. The injector syringe must always be angled *downward* when it is connected to the hub of a catheter or connecting tubing for an injection. The downward angle forces any air which might be trapped in the injector tubing or injector syringe to rise to the back end of the injector syringe. When the injector syringe is attached directly to the catheter hub, the injector head is *always* positioned above the level of the hub of the catheter in order to assure that the *tip* of the injector syringe is pointing downward.

Fortunately, the “injector head” of the modern MedRad (MedRad, Inc., Indianola, PA) and Liebel-Flarsheim (Mallinckrodt Inc., Hazelwood, MO) angiographic injectors can be separated from the large, bulkier, control apparatus of the injector. This allows the injector head to be mounted separately and away from the control unit. Mounting the injector on a long, movable, ceiling-mounted arm positions the injector head well above the surface of the catheterization table and allows it to be moved to any location about the table. A ceiling-mounted injector does not occupy any floor space and there is less danger of the sterile field or the operator being contaminated when the injector is being attached to, or while it is attached to, the catheter. The separate control unit can be positioned across the catheterization room away from the catheterization table or, preferably, even in a separate, but adjacent control room.

A less satisfactory arrangement is to have the separate injector head mounted on a mobile floor stand. However, the floor stand occupies valuable floor space wherever it is positioned and it must also be moved about the room and positioned immediately adjacent to the catheterization table for injections. This positions the stand very close to the side of the patient and necessitates that the injector extends over, and very close to, the sterile field. With a rigid attachment to the floor stand, the injector head cannot be raised much above the level of the catheter hub in order to keep the tip pointing downward. Some of these disadvantages can be obviated by the use of very long connecting tubes between the injector syringe and the catheter.

Adjustable radiation protection screens

In addition to the regular use of lead aprons and optimal X-ray techniques, supplemental X-ray protection screens should be used during every catheterization procedure. Most of the radiation to the operating physician originates from the scatter, which emanates out of the patient’s body *above* the catheterization table. The most effective way of

minimizing this radiation to the operator is by the use of a leaded glass screen placed between the patient's body and the operating physician. The preferred screen for the protection of the operating physician is suspended on a long articulated arm from the ceiling above the catheterization table. In this way the screen, covered with a sterile, transparent drape, is moved between the patient and the operator without occupying any "real estate" on the floor of the room and without contaminating the field.

Similar protective leaded glass screens are available on floor mounted stands, which move on casters; however, the floor screens occupy valuable floor space and when used near the catheterization table, interfere with angulation of the X-ray tubes. Large, free standing, transparent, leaded glass X-ray screens, mounted on casters, are useful for the protection of personnel not working directly at the table. The additional personnel who benefit the most from these screens include the anesthesiologist, the circulating nurse/technicians and respiratory therapists.

Cardiac output computer

Determination of the cardiac output is often required during the catheterization of pediatric and congenital heart patients. Although a precise cardiac output is not necessary for calculating *relative* shunts and obvious gradients, when the calculations of absolute flow and resistances are necessary, an accurate cardiac output becomes mandatory. Our cardiac catheterization laboratories now use a thermodilution technique with a small, dedicated, Dualtherm™ Cardiac Output Computer (B. Braun Medical Inc., Bethlehem, PA) designed specifically for calculating thermodilution cardiac outputs. The thermodilution apparatus is relatively small and is mounted on a small mobile cart. When a cardiac output is to be determined, the computer is connected to the specific thermodilution catheter (B. Braun Medical Inc., Bethlehem, PA) on the catheterization table with a sterile, reusable cable, which extends directly from the computer to the catheter. This small cart is moved close to the table for cardiac output determination and is parked well away from the catheterization table when not in use.

"In-room" consumable equipment storage

The great bulk of the consumable equipment, including the back-up supply of the most frequently used items, is stored in a *separate*, dedicated storage room, which is situated immediately adjacent to the actual catheterization room. At the same time, a limited supply of multiple sizes of very frequently and repeatedly used sterile consumable items including percutaneous needles, a variety of guide wires, sheath/dilator sets, syringes, the most frequently used catheters and even gloves are stored directly in the

catheterization room, but in mobile carts. While all of the consumable equipment could be stored in the adjacent storage room, the repeated retrieval of very frequently used items from a separate, even though adjacent room, during the case, reduces the functional efficiency of the laboratory very significantly.

Storage of the "high use" expendable materials actually within the room maximizes the efficiency for the frequent retrievals. Specifically configured, mobile storage carts provide the most effective vehicle for this in-lab storage of the frequently used consumables. These can be moved in and out of the room for cleaning, for restocking with new supplies or when the particular items on that cart are not being used at all. These carts can also be moved easily to accommodate a reconfiguration of the arrangement of the room according to the various introductory sites for the catheters or according to the type of procedure being performed.

The mobile storage carts maximize the usable space of the room as opposed to the traditional, fixed cabinets along the walls of the room. Any fixed, built-in cabinets for storage within the catheterization room represent "wasted" floor space, which is lost permanently and cannot be "adjusted". Each row of fixed cabinets or counters reduces the functional width or depth of the catheterization room by at least three feet and reduces the total floor space of the catheterization room by this width times the length of the wall(s) covered with cabinets! Built in cabinets do not allow even minor reconfiguration of the room for different procedures.

"Mobile" equipment stored outside of the catheterization room

There are other pieces of mobile equipment that are shared between several catheterization rooms and stored within the general area of the catheterization laboratory, but preferably just outside of the actual catheterization room. Each piece of this equipment requires space for storage outside of, but adjacent to, the actual catheterization room and, when the equipment is in use, additional space must be provided for it in the catheterization room itself. Among this ancillary equipment are included a separate, but constantly available, 2-D echo machine, a radio frequency generator, an oxygen consumption apparatus with its constant air withdrawal system and several "hoods", an echo console for intravascular ultrasound (IVUS), transesophageal echo (TEE) and/or intravascular echo (ICE), a Laser™ generator and possibly a cardiac "mechanical assist" device. When used, most of these pieces of equipment must be positioned immediately adjacent to the catheterization table. At the same time, the location of this equipment while it is being used should not interfere with the catheterizing physician's access to

the patient or the overall mobility within the room. This requires a greater overall planned width or depth to the room in order to prevent severe side-by-side crowding at the table side.

2-D Echo machine

A 2-D echo machine capable of transthoracic scanning of the pericardial space should be available in the catheterization laboratory immediately for emergency situations. This does not have to be the latest nor the most sophisticated echo machine available but it must be functional. This echo machine is required in addition to, and separate from, the TEE/ICE console, which usually is a special console utilized specifically for TEE and/or ICE and is brought to the catheterization laboratory only when TEE and/or ICE is/are used. Much of the time, the TEE/ICE machine may be needed elsewhere in the hospital and, in turn, may not be available for some time or be physically far from the vicinity of the catheterization laboratory. The separate, always available 2-D echo machine is primarily for screening patients who deteriorate either acutely or unexpectedly. This is particularly important when screening for suspected cardiac tamponade. The added time needed to transport an echo machine to the catheterization laboratory from an area outside of, and remote from, the immediate catheterization area represents a delay in confirming a diagnosis, which could easily represent the difference between a successful and an unsuccessful resuscitation.

Radio frequency generator

Pediatric cardiac catheterization laboratories now require a dedicated radio frequency (RF) generator, which is designed specifically for the perforation of tissues. Although this unit may be used only 6–12 times per year, the infants in whom an RF generator is used are not “scheduled” and often have a critical time window for their treatment. The BMC Radio Frequency Generator (Baylis Medical Co. Inc., Montreal, Canada), specifically for perforation, is quite small and can be stored outside of the actual catheterization room when not being used. When used in any particular procedure it is placed on a small, temporary cart adjacent to the catheterization table and connected to the RF catheter (Baylis Medical Co. Inc., Montreal, Canada) with a sterile reusable cable.

Oxygen consumption apparatus

The MRM-2 Oxygen Consumption Monitor (Waters Instruments Inc., Rochester, MN) for measurement of oxygen consumption is a gas analyzer in conjunction with several different hoods and a vacuum pump/blower used

to draw air through the hoods. In most laboratories, the apparatus is used infrequently and, as a consequence, is (should be) stored in an adjacent area, out of the catheterization room. The apparatus is cumbersome; it covers the patient’s head, neck and upper thorax and is fairly disruptive to the usual catheterization procedure. When an oxygen consumption determination is to be performed on a patient during a catheterization procedure it is planned ahead of time and the specific arrangements are made for the oxygen consumption measurement when the patient is being placed on the catheterization table. The patient’s head and neck are positioned on a flat surface on the catheterization table with no pillow beneath their head. There can be no catheter lines entering the neck and the patient cannot be intubated or receiving oxygen or general anesthesia while oxygen consumption is being measured.

Intravascular ultrasound and intracardiac echo equipment

Currently intravascular ultrasound (IVUS) and intracardiac echo (ICE) imaging are used frequently in many pediatric and congenital catheterization laboratories. The particular consoles from Acuson, Mountain View, CA or Boston Scientific, Natick, MA, which are used for this imaging are quite large. The consoles are usually stored out of the actual catheterization room and brought into the laboratory only when needed for a specific case. The catheter for ICE is a 10–11-gauge French catheter and usually is introduced from a femoral vein, while the catheters for IVUS are smaller and can be introduced into a vein or artery from a femoral or jugular access site and can be introduced from either arm. The catheters are usually attached to their respective console with a long connecting cable within a long sterile sleeve. The physician operating the console is not necessarily the catheterizing physician who is maneuvering the catheter. As a consequence, the machines (consoles) for these procedures usually do not have to be immediately adjacent to the catheter introduction site, but do require a relatively large space, relatively close to the catheterization table in the general area where the imaging catheter is introduced. Like the TEE, a remote or slave monitor is usually necessary in order for the catheterizing physician to visualize the intravascular echo images conveniently.

Laser™ generator

A Laser™ generator (Spectranetics, Colorado Springs, CO) is used for lead extractions and some purposeful perforations. It is another very large piece of equipment, which is used in a pediatric/congenital cardiac catheterization laboratory only occasionally and, when moved into the room, requires significant additional space adjacent to

the catheterization table. The Laser™ generator is stored outside of the catheterization room or even away from the laboratory as a shared piece of equipment between several services or even institutions. The use of the Laser™ is scheduled well ahead of time and the generator is moved into the laboratory for the specific procedure. Special precautions for eye protection are required for all personnel who are, or might be, in the room for the procedure. Considerable rearranging of the equipment in the room is required during these isolated and rare circumstances.

Extra cardiac membrane oxygenator (ECMO) or other left ventricular assist device (LVAD)

An even more rarely used piece of very large and cumbersome adjunctive equipment which may become more common and even essential in the future catheterization laboratory is one of the cardiac assist devices including an ECMO apparatus, an intra-aortic balloon pump or even an LVAD. When an assist device is necessary, it likely would be as an emergency. Although the equipment for these procedures would have to be moved from the operating room or intensive care area, it would not be expedient to have to move other equipment which is being used in the catheterization laboratory out of the laboratory, or to have to rearrange the catheterization laboratory very significantly in order to bring these large pieces of emergency equipment to the patient rapidly during such an emergency. A potential physical “corridor” to the table, and place for this equipment, should be considered ahead of time when a catheterization is planned on a patient who might be a potential candidate for such therapy.

Electrophysiology equipment

The pediatric/congenital electrophysiologic (EP) laboratory contains additional very large pieces of equipment which, unlike the catheterization table itself, are not fixed structures in the room, but, at the same time, are not particularly mobile and take up considerable additional fixed space. This equipment varies with each EP laboratory, but at a minimum includes a separate computer and monitor, a separate recorder, a stimulator, a radio frequency generator for ablations, multiple additional CRT monitors and additional mobile storage cabinets for the frequently used, special EP consumables. The Laser™ generator for lead extractions is more likely to be used and stored in the EP laboratory. The extra EP “capital” equipment often has a space requirement equivalent to the space of a separate control room. Usually this equipment is housed in, and used directly within the catheterization room. This extra space should be included in the basic design of the catheterization room which is to be used for electrophysiologic procedures.

Support areas for the catheterization room(s)

The actual cardiac catheterization room is not a “free standing”, independent or isolated room, which can be placed randomly at the convenience of any available space. Each catheterization room requires a significant amount of space which must be immediately adjacent to the catheterization room, for the logistical, mechanical and personnel support for the operation of the actual catheterization room. This support space plus the catheterization room(s) make up the catheterization suite. The support space occupies more square footage than the catheterization room(s). The support space ideally includes a separate control room for each catheterization room, a large room for the storage of the majority of the consumable equipment, a separate electrical equipment room or “bay” for the X-ray generators, controls and high-tension switches, a patient holding/preparation area, an administrative support area, a record/angio review/work area, an on-site storage area for “active” patient records and angiograms, a biomedical service/supply area and a separate procedure room for procedures other than X-ray which require monitoring (e.g. phlebotomies, thoracentesis, transesophageal echocardiograms).

Control room

The control room houses the physiologic monitoring equipment, computer recorder and the controls for the X-ray system for each specific catheterization room. In addition, each control room contains remote monitors of the CRT screens which are in the catheterization room, the controls for the angiographic injector, the computer(s) which is/are connected to the hospital system, the digital X-ray recording system, a digital disk copier, printers for physiologic records, the computer log of the procedure, and hard-copy printers for X-ray images, all with adequate space for at least two nurses/technicians to function comfortably. An area 10 to 11 feet wide and as long as the width of the catheterization room (e.g. 10 × 24 feet) provides a reasonable sized control room with room for some fixed counters and cabinet space in addition to the monitoring equipment. In addition to a good view of the entire catheterization room, including the entire catheterization table, and clear voice communication between the catheterization room and the control room, the personnel in the control room should have direct and easy physical access into the catheterization room.

The control area preferably is *not* situated *within* the actual catheterization room. The control/monitoring/recording equipment takes up a large amount of valuable floor space, which should not be taken from the actual

catheterization room. The control room equipment generates noise, accumulates dust and is operated more effectively in a clean, but non-sterile, environment. In addition, when the control room equipment is located within the catheterization room, it exposes the nurses/technicians who operate it to extra and unnecessary radiation. At the same time, the control room must be *immediately* adjacent to the catheterization room. The orientation of the catheterization table diagonally across the catheterization room facilitates a view of the entire length of the patient on the table whether the control room is directly at the end or along the side of the catheterization room. The control room usually is *not* a sterile area and can have additional space in it, which serves as an observation area for consultants/visitors.

A shared central control room between two or more catheterization rooms is seen occasionally, but is not an optimal arrangement. Except for a questionable economy of space, there is no justification for a combined or shared control room. None of the actual electronic control equipment in the control room is shared between separate catheterization rooms. Much of the communication between the separate catheterization rooms and the control room and within the control room is verbal. When the control equipment and personnel from two or more laboratories are grouped together in one room, there are continual distractions, the communication becomes confused and the working environment becomes very congested and noisy.

Consumable equipment storage room

The *majority* of the consumable equipment (catheters, introducers, wires, dilation balloons, special devices, etc.) is stored outside, but immediately adjacent to, the actual catheterization room. For a laboratory performing therapeutic catheterizations on pediatric and adult congenital heart patients, this requires a huge amount and variety of consumable equipment which, in turn, requires a very large storage space, which is equal in size to the optimal sized catheterization room (roughly 32 × 24 feet). Fortunately two, or even three, separate catheterization rooms do not require significantly more consumable equipment and additional storage space for the consumable equipment than a single laboratory. If there is more than one catheterization room, it is most efficient to have a single storage room for the consumables adjacent to, and connected to, all of the separate catheterization laboratories (rooms) with convenient access to each of the laboratories. Because of the large amount of very expensive consumable material required for a pediatric/congenital catheterization laboratory, the storage area must be absolutely secure.

The storage room requires an organizational plan or arrangement for inventory control which (1) keeps track

of each item used to facilitate the expedient reordering of used items and, (2) obligates the use of the older items before newer, more recently acquired items in order to avoid the problem of having to discard new and unused items because of material or sterility expiry dates. This organization of the inventory is even more critical when several or more catheterization rooms are drawing supplies from the same storage source.

A catheterization laboratory should have both a blood gas analyzer such as an ABL 700 Radiometer (Radiometer, Copenhagen, Denmark) and an activated clotting time (ACT) machine (Hemo Tec, Inc., Englewood, CA). Both of these machines can be shared between several or more catheterization rooms. These machines are fixed in location and when shared, they are housed conveniently in a central consumable storage area, which is adjacent to all of the actual catheterization rooms. This equipment must be in close proximity to each catheterization room but, preferably, must not be within the catheterization room itself. Under usual circumstances this equipment is used only two or three times during an entire catheterization procedure. Both the blood gas and ACT machines require regular maintenance and calibration by biomedical personnel who normally function more proficiently in a non-sterile environment. When these machines are not in the actual catheterization room, any maintenance/calibration can be performed on them while a catheterization is in progress. Rarely, blood gas machines are used to calculate all of the blood oxygen saturation determinations. In that situation, the blood gas machine should be physically in the catheterization laboratory.

A separate, X-ray equipment room or "bay"

It is now *essential* that modern X-ray generators and X-ray power supplies are housed in a dedicated equipment room, which is completely separate from the catheterization room. There no longer is a place for the cabinets for the X-ray generators, controllers and high-tension "switches" to be located within the actual catheterization room. In addition to the physical space occupied by the high-tension generators and other X-ray electronic equipment, this equipment requires a separate and efficient refrigeration/air conditioning unit to allow continuous, extra and extreme cooling of the X-ray and other electrical components in order to counteract the excessive heat generated by it. The cool environment is essential for the day-to-day stability and operation of the sensitive equipment and in order to maintain the durability of the very expensive electrical equipment. When the electrical equipment is situated in the catheterization room, an environmental temperature which is cool enough to keep the equipment adequately cooled is far too cold to maintain the body temperature of a patient.

Although the “equipment bay” is a separate room, because of the limitations of the maximal lengths of the high-tension cables connecting the X-ray tubes to the generators, it must also be in close proximity to the actual catheterization laboratory. Assuming the “geometry” can be solved for situating more than one catheterization room adjacent to the equipment bay, a single equipment bay can house the generators and power supplies of two or more catheterization rooms while using the same additional cooling system. The equipment bay needs a lot of wall space for the modern digital electronics so that a relatively long but narrow room, for example 10 × 32 feet, will suffice to hold the heavy electronic equipment for two biplane catheterization rooms (Siemens Medical Systems, Inc., Iselin, NJ) as well as the extra cooling equipment.

In addition to the cooling requirements, even the latest digital and computerized catheterization laboratory X-ray generating equipment still takes up a large amount of space and, if positioned within the actual catheterization room, would reduce its functional width by at least two feet in depth along one entire, long wall. When the generation equipment is within the sterile catheterization room, access to the equipment for maintenance or even minor resetting of circuits is restricted to times when the room is not in operation. Like the electronic equipment in the control room, the X-ray generating equipment has huge areas for attracting and collecting dust, which is not acceptable in a “sterile” working catheterization room.

Preparation, holding and recovery area(s) for patients

Patients do not enter directly into the cardiac catheterization laboratory from “outside”, nor do they go directly home after a catheterization. With many pediatric and congenital heart cardiac catheterizations now being performed as outpatient or “day-surgery” procedures, an area is required for the admission of the patients for the catheterization procedure, their preparation for catheterization and the administration of premedications. When the catheterization laboratories operate adjacent to, or in conjunction with, the cardiovascular operating rooms, the same preparation/holding area can be used to admit the patients for both the catheterization laboratories and the operating rooms. The total size of the “holding area” depends upon the number of procedure rooms (catheterization labs or operating rooms), which are being supported.

Each bed space in a “holding/admitting” area should be capable of monitoring and recording several leads of an electrocardiogram, a pulse oximetry display, a display of the patient’s body temperature and the capability of displaying at least one pressure monitoring line. The physical space of each “holding bed” must comply with

standards for recovery room beds. Each bed requires piped in oxygen, compressed air and suction. The holding area must have a separate “crash cart” including emergency cardiac medications, intubation and temporary ventilation equipment as well as a cardiac defibrillator. All of the facilities and equipment for drawing blood samples as well as starting and maintaining intravenous lines must be available in the holding area. All of the beds can be in one open area, but must be separated from each other by at least curtains or screens. Since some patients may remain in the area for a relatively long period of time awaiting their catheterization or surgery, a television or “play station” is made available for at least half of the beds.

The number of beds and the size of this area, obviously, depend upon the number of catheterization rooms (and operating rooms if the area is shared), any function of the area besides admitting and holding, and the total number of patients expected through the area per day. For patient preparation and premedication, one bed per catheterization procedural room *and* one bed for each operating room are sufficient. This allows for the simultaneous preparation at the beginning of the day of all of the “first” patients for each of the procedural rooms and allows each procedural room to start at approximately the same time when desired. Patients who are scheduled for catheterization (or surgery) as second, third or later cases are scheduled to arrive at the holding area later according to a staggered schedule. This allows a bed for each patient, time to admit each patient comfortably, prepare them for the procedure and to have them totally prepared and sedated by the time the procedure room is ready to start.

A four to six hour recovery/observation period is mandatory immediately post-catheterization for cardiac catheterization patients. The patient should have close monitoring by experienced nurses during that time immediately after a cardiac catheterization. Ideally, this monitoring is accomplished in a cardiac recovery area or cardiac intensive care unit. However, if the cardiac catheterization laboratory is in a location remote from the cardiac recovery/intensive care units, the holding area can be adapted to serve as an observation/recovery area for the patients post-catheterization. With an adequate number of beds and the space and monitoring equipment to be used for patient recovery post-catheterization already established, the same area used for the patients’ admission can be expanded to a recovery area. In that circumstance, because of the overlap of the patients arriving for their procedures with the patients who are recovering, the “recovery” beds in the area should be separated from the “admission” beds more solidly than with just curtains. A recovering patient who is uncomfortable, vomiting or having more serious problems, is extremely upsetting and frightening to a patient who is about to undergo “the

same" procedure! When the holding area is used for post-catheterization recovery, the nursing staff is larger, the nurses need additional training and experience in the recovery of catheterization patients and the functioning "hours" of the holding area must be extended and very flexible according to the anticipated procedures for the day.

Administrative and general support areas

A liberal amount of additional space is required *within the general catheterization area* for the general administrative support of the catheterization laboratory. This support area includes the working areas for the catheterization laboratory manager and secretarial/administrative assistants. They should be located in close proximity to the actual laboratory in order to support the minute-to-minute activities of the laboratory including the changes in scheduling and assignments during each day. The administrative support area also provides a work area for the nurses, technicians and physicians to review and compile the catheterization records and angiograms, space and the equipment for copying these materials and space for the temporary storage of, at least, the most current and "active" catheterization records and angiograms. For the support of two or more laboratories, this requires working space for two or more personnel. This area can be relatively long and narrow in order to be positioned immediately adjacent to the catheterization laboratories, for example 10 to 11 feet by 32 feet in length.

The catheterization laboratory area must have adequate and convenient toilet facilities, which include sinks and a shower along with secure lockers and changing space for all of the personnel working in the catheterization area. The personnel should not have to leave the general area of the catheterization laboratories to use the toilet or changing facilities. Easy access to a supply of "scrubs" in a convenient changing/locker area within the catheterization suite encourages the personnel to change into scrubs while in the catheterization laboratories, but, at the same time, encourages them *not* to wear the scrubs out of the hospital.

The overall cardiac catheterization area needs a separate break or relaxation area for all of the personnel who work there. The personnel in the catheterization laboratory work in a continually stressful atmosphere and, frequently, at a continual and frantic pace. At least a short intermittent break out of the catheterization room improves the working atmosphere in the room. When this "break room" is still within the area of the catheterization suite, it allows the personnel to have time out of the actual rooms without losing "transit" time to and from a break area and without the personnel having to change out of their laboratory scrubs.

Cine/angio/data review area

Each catheterization suite requires an area for the physicians to review and analyze the data and the angiograms from the current catheterizations. The review area should have space to accommodate up to four or five physicians at a time as well as a large counter space for the review and measurement of the paper tracings of the recorded pressures, which when stretched out extend for several meters. The review area requires at least one computer, which is in communication with the catheterization laboratory as well as the information systems of the hospital including the hospital X-ray and echo systems. This (or these) computer(s) also should be in communication with the on-line, digital storage system for the digital angiograms from the catheterization laboratory.

The review room requires specific and usually separate equipment for the review of "outside" angiograms as well as those generated in the catheterization laboratory itself. The common transferable, digital media at the present time is the DICOM encoded compact disk (CD). This requires a digital viewer/review station, which can read all medically encoded DICOM digital data. Although all major medical manufacturers supposedly comply with a single DICOM standard, occasionally separate software is required in the CD reader or a completely separate computer/review station is necessary to read CDs from different systems/manufacturers. Since many of the previous, older, angiographic studies on the current patients were recorded on cine film and some existing cardiac catheterization laboratories are still recording on cine film, the reviewing area requires a functioning cine film viewer (Tagarno of America, Inc., Dover, DE).

The review area must have some space designated for the storage of the catheterization reports and angiogram of patients who are currently hospitalized, or who will be hospitalized in the near future. A copying machine for records, catheterization diagrams and digital angiograms improves the efficiency of the area and helps to keep permanent records intact.

Biomedical support area

With the total dependence in a modern catheterization laboratory upon the large variety of both simple and very complex electro-mechanical equipment, all cardiac catheterization laboratories are equally and totally dependent upon biomedical support being readily available in order to operate the cardiac catheterization laboratories daily and continuously. Ideally the biomedical personnel for the cardiac catheterization laboratory are a part of the catheterization laboratory personnel, and their primary responsibility is to the catheterization laboratory. There should be adequate space in the vicinity of, or actually in,

the catheterization laboratory suite for the biomedical personnel to work on the mobile equipment. The biomedical area must include space to store the testing and repair equipment as well as pieces of frequently needed and essential "spare" equipment. When there is more than one catheterization laboratory or other "high-intensity electrical areas" (operating rooms, intensive care areas) in close geographical proximity, there is adequate justification for specific biomedical engineers who are knowledgeable in that particular equipment to be assigned to the catheterization laboratories.

Any delay in the investigation and repair of an equipment malfunction, no matter how minor, results in an equivalent "down", or "inactive time" for the room, which includes three or more salaried nurses/technicians and one or more physicians who would be working in that room. A malfunction of a piece of equipment often requires a "repair" which is as simple as resetting a relay or switch and actually takes only seconds for a knowledgeable person to correct. At the same time, the relay may be located in a "high-tension" cabinet containing very complex electronics and, as a consequence, should be manipulated only by experienced biomedical personnel. An otherwise short delay is prolonged unnecessarily when the biomedical support who is capable of the simple "repair" or "resetting" is located any distance (and time) from the catheterization area. An active, fully scheduled, cardiac catheterization laboratory cannot afford any significant "down time". Any equipment failure during operating hours results in the rescheduling of the patients with a frequent "domino" effect on other patients and services throughout the hospital, in addition to the obvious costs in personnel "down time".

A separate "minor procedure" room

Depending upon the size of the cardiology service, there are a variable number of procedures which require monitoring, sedation and, occasionally, even general anesthesia. These procedures include phlebotomies with colloidal volume replacement, "tilt table" and other vaso-motor electrophysiologic testing, transesophageal echocardiography under general anesthesia, pleural taps and drainage with or without chest tube insertion, some pericardial taps and even some difficult intravenous or intra-arterial lines. The "interventional", "intensivist" or "catheterizing" physicians frequently perform these procedures. Although these procedures have been, and can be, performed in catheterization laboratories, they generally do not require *all* of the elaborate equipment and personnel of a catheterization laboratory.

Ideally, a separate "procedure room" is available in the immediate area of the catheterization laboratories/holding area. This room needs to be large enough to

accommodate the procedure table, a sterile work table for the physician, any ancillary large equipment (e.g. a TEE machine, an anesthesia machine) and area for personnel to function in the room. The procedure room should have monitoring available with the capability of permanent recording of the ECG, pulse oximetry, a periodic recycling cuff blood pressure apparatus and at least one pressure transducer and recording channel for an indwelling line when desired. Piped in oxygen, compressed air and suction are essential. The procedure table in this room is an operating type of table, capable of tilting or there is a separate "tilt table" which can be moved into the room. The procedure table is lit with a high-intensity, ceiling-mounted, mobile "operating room" light. This room should have a mobile equipment cart to hold the consumables for any procedure being performed. The procedure room must have immediate access to a separate "crash cart" with intubation equipment, resuscitative drugs and fluids and a defibrillator. If the procedure room is *immediately* adjacent to the "holding" area, the emergency cart is shared with the holding area. Patients who are treated in this procedure room need admitting and frequently a recovery time similar to a catheterization patient.

Film processing room

A film processing room (area) is no longer necessary in a cardiac catheterization laboratory with digital X-ray equipment. A film processing room is still necessary in laboratories with older X-ray equipment which are using cine film as the recording medium. Although the image is produced by X-ray energy, cine-angiography film is a photographic film and is processed in a separate processor and with completely different techniques from the processing of X-ray film. Cine film processing is complex, time consuming, space occupying and environmentally polluting, all of which justifies upgrading cine film X-ray equipment to a digital system.

A film processing area includes not only a room for the film processor, but also a dark-room and a separate room to store the processing chemicals. The film processors are fairly compact but very complicated and require plumbing attachments from the chemical tanks and separate attachment to a special drainage system for the highly acidic and toxic developing chemicals. The processor requires constant maintenance in order to obtain the optimal processing of each roll of film. The daily maintenance includes adjusting the composition and temperature of the chemicals, assurance that all of the pumps and drives are functioning properly, and the cleaning of the multiple separate tanks and rollers in the processor. In addition to being consumed by the processor, the processing chemicals deteriorate with time and must be changed regularly regardless of the use of the processor. Possibly by the time

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