Gianfranco Butera
Massimo Chessa
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Editors

Atlas of Cardiac Catheterization for Congenital Heart Disease

Springer

EXTRAS ONLINE

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Preface

A picture is worth a thousand words!

And think about the impact of videos!

Moreover, we are in the era of the image and of "liquid" life and society.

The ATLAS version of the handbook of interventional congenital cardiology goes exactly in that direction. The authors made the meaningful effort to keep a step further and develop an agile tool.

More than 450 images and 120 videos detail procedural steps and technical issues and are provided for reader's joy and learning.

A useful learning tool is now available worldwide!

London, UK	Gianfranco Butera
San Donato Milanese, Italy	Massimo Chessa
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Part XI Future Directions

About the Editors

Gianfranco Butera, MD, PhD, FSCAI Consultant Pediatric Cardiology of the Evelina Hospital in London. Lead of Congenital Interventional Cardiology of St Thomas'-Evelina Hospital in London (UK). He has been Chef de Clinique at Hôpital Necker Enfants Malades - Paris and worked as Consultant for Pediatric Cardiology and GUCH cardiology at the Policlinico San Donato IRCCS in Milan (Italy). He studied at the Catholic University of Rome, specialized in Pediatric Cardiology, and completed his training at the Hôpital Necker Enfants Malades in Paris, France, with Prof. Kachaner and Prof. Bonhoeffer and obtained a postgraduate degree in Pediatric Cardiology from the Universitè René Descartes, Paris V. He is a fellow of the GISE, SICP, AEPC, SCAI, and COMET and serves on the executive council of two charity associations. He has served as chairman of the Working Group of interventional cardiology of the AEPC. He has been a visiting professor at various universities including Harvard, Bordeaux, and Padova, and his clinical and research interests are focused on interventional cardiology in children and adults with congenital heart diseases. In addition, Prof. Butera is a reviewer for 15 international journals and Case Report Editor for Cardiology in the Young. He has authored more than 180 papers in peer-reviewed journals and has edited books on interventional and fetal cardiology. With Springer he co-edited the book *Cardiac Catheterization for CHD* and a book on fetal and hybrid cardiac procedures.

Massimo Chessa, MD, PhD, FSCAI, FESC main clincial focus is on management and intervention in children and adults with congenital heart diseases; since his PhD he has been working as a Consultant in Congenital Heart Disease IRCCS-Policlinico San Donato Pediatric Cardiology Department and Adult with Congenital Heart Defect Unit, practicing more than 500 catheterizations per year (80% of which interventional). He is leader of the ACHD Program devoted to adults with congenital heart defects, senior researcher, and involved in many projects for International and Humanitarian Cooperation. He has been visiting fellow in France and in the UK and is President of AICCA (Italian GUCH Association www.aicca.it). He has authored more than 150 publications in peer-reviewed journals, 8 chapters in books, has been editor of two volumes for Springer Verlag on *Adult Congenital Heart Disease* and *The Right Ventricle in Adults with Tetralogy of Fallot*, and is editor of the book series devoted to ACHD endorsed by the ESC and AEPC ACHD/GUCH Working Groups.

Andreas Eicken, MD, PhD, FESC is a consultant for patients with congenital heart disease (from infant to adult age) at the German Heart Centre, Munich, Germany. He studied medicine in Münster and Lübeck, specialized in pediatrics in Munich, and completed his cardiology training at the German Heart Centre in Munich with Konrad Bühlmeyer and John Hess as teachers. Andreas Eicken attended the ESC nucleus working group on Adults with Congenital Heart Disease for eight years and served as a president of that working group from 2014 to 2016. Currently, he is a council member of the AEPC board. Andreas Eicken published over 130 papers in peer-reviewed journals and is currently the head of the catheterization laboratory for children and GUCH patients at the DHM in Munich.

John D. Thomson, MD, FRCP, FSCAI is a consultant cardiologist specializing in the interventional treatment of children and adults with congenital heart disease. He studied in the UK and Australia and has worked in consultant positions in Guy's and St Thomas Hospital in London and the Yorkshire Heart Centre in Leeds where he is the current head of department. He wrote his MD thesis on the neurological benefits of interventional catheterization compared with standard surgical therapy. He has been the honorary secretary of the British congenital cardiac association and is the current President of the AEPC intervention working group having previously been the secretary of that association. He leads a high volume interventional unit and pioneered a number of treatment modalities including ductal stenting.

Part I

General Issues

Angiography: Radiation Exposure and Standard Projections

1

F. Gutierrez-Larraya, C. Abelleira, C. Balbacid, and A. Sanchez-Recalde

1.1 Introduction

1.1.1 Radiation Exposure in Catheterization Laboratory

The large amount of collective effective dose is related to diagnostic and interventional catheterization. Many factors contribute to a relatively higher level of exposure in pediatric patients. These factors include age, body size, distance between hands and body and X-ray generator, configuration of the X-ray equipment, number of cases per day, and length of study. Both patients and working staff are at a potential risk to radiation. In particular children are at higher risk after exposure to medical radiation. In fact, for any given dose, children are three to six times more sensitive to the induction of cancer as they have more rapidly dividing cells and longer life expectancy than adults. Also, for a given procedure, dose is larger in a small infant than in an adult, and organs are closer resulting in more radiation dose. See Figures 1.1–1.14 and Table 1.1 for better understanding.

1.1.2 How to Reduce Radiation Exposure During Invasive Cardiac Procedures

Pre-procedural Planning:

1. Use dosimeters and shielding.
2. Know radioprotection principles.
3. Know your equipment.
4. Plan your study.

Procedure:

1. Follow the "as low as reasonably achievable" (ALARA) principle.
2. Limit fluoro and cine.
3. Store fluoro use as much as possible.
4. Use the lowest frame rate.
5. Keep the intensifier or flat panel detector as close to the patient as possible.
6. Use the lowest degree of magnification required for accurate interpretation.
7. Minimize radiographic beam time ("cine" acquisition creates 12- to 20-fold higher dose intensities than fluoroscopy mode).
8. Use collimation.
9. There are less-irradiating angulations: 20° right anterior oblique gets the lowest patient DAP and cranial and caudal angulations raise the doses significantly and are maximum in left lateral angulations.
10. Working for more than 6 h increases radiation exposure to 28%.
11. Remember an adequate use of filters, especially for small (<15 kg), and the simpler rule than doubling the source-to-operator distance will decrease the operator dose to approximately one quarter.
12. Operator and personnel exposure are directly related to the dose area product: when operating in a biplane cine-acquisition mode, scattered radiation multiplies by a factor between 5 and 21.

The original version of this chapter was revised. A correction to this chapter can be found at https://doi.org/10.1007/978-3-319-72443-0_46

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-319-72443-0_1) contains supplementary material, which is available to authorized users.

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1.2 Angiographic Projections

1. Plan your case in advance, and use informations coming from other imaging modalities (echocardiography, CT, MRI).
2. The main idea is to get axial, non-overlapped, or foreshortened profile of the various structures; many and different angulations will be needed with great variations for the same structure or disease in different patients.
3. Projections used for angiocardiography include frontal, lateral, right, and left oblique, with or without axial (craniocaudal or caudocranial) angulations. 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, but possible combinations are endless with many local or personal variations.
4. Useful "rules of thumb": (a) achieve the correct degree of steepness or shallowness; (b) choose the degree of cranial or caudal tilt.
5. Very important rule: get useful and not only fine pictures!

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                                    Exam Protocol
-----------------------------------------------------------------------------
Patient Info:
Name: [redacted]                                 Sex:: F  ID: [redacted]
-----------------------------------------------------------------------------
Pos. d. paciente:  HFS                                     03-Sep-10 09:19:58

2    CARD         FIXED    LV 3040                  6s  30F/s  03-Sep-10 10:32:33
B  73kV   66mA   3.2ms  0.0CL small     25cm   26.1µGym²  5.0mGy  90LAO   1CAU 182F

2    CARD         FIXED    LV 3040                  6s  30F/s  03-Sep-10 10:32:33
A  73kV   55mA   3.3ms  0.0CL small     22cm   42.7µGym²  4.8mGy  13LAO   4CRA 182F

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***Datos de expos. acumulada***                            03-Sep-10 12:07:26
Fis.: Dr[redacted]    Expos.: 4     Fluoro:  10.5min Total:  256.2µGym²  35.4mGy
A    Fluoro:     5.5min     85.5µGym²     9.2mGy           Total:  167.1µGym²  18.4mGy
B    Fluoro:     4.9min     37.8µGym²     7.1mGy           Total:   89.1µGym²  16.9mGy

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Fig. 1.1 Terminology. Total *air kerma (K, Gy units)* is the procedural cumulative X-ray energy delivered to air at the interventional reference point and is associated with threshold-dependent deterministic skin effects. *Peak skin dose* is the maximum dose received by any local area of the skin; it is not measured but is derived from total air kerma and also reflects deterministic effects. The International Commission on Radiological Protection (ICRP) recommends the use of *effective dose (E)* to evaluate the effects of partial exposure and relate this to the risk of equivalent whole-body exposure. So, it is used to express detriment to whole body if only a part of the body is exposed. The E characterizes stochastic cancer risk. The unit for *effective dose is the sievert (Sv)*. One Sv carries a 4% chance of developing a fatal cancer in an average adult and a 0.8% chance of hereditary defect in future offspring. Modern cardiac interventional procedures, angiography and interventions, produce effective doses of 4–21 mSv and 9–29 mSv. Published effective doses for pediatric catheterization range from 2.2 mSv to 12 mSv. *Dose area product* (DAP)—the standard unit is Gray-square centimeter—is defined as the absorbed dose multiplied by the area irradiated, and it is the measure reflected in angiographic studies indicating the total X-ray energy delivered to the patient as a result of fluoroscopy and cine-film sequences. It is a marker of stochastic and no deterministic risk. Coronary angiography and interventions produce DAPs in the range 20–106 Gy cm^2 and 44–143 Gy cm^2, respectively. In order to estimate the risk of radiation-induced sequelae, the dose area product (Gy cm^2) must be converted to the effective dose (mSv). In computed tomography (CT), *dose-length product* (DLP) is the standard dose measurement reported, expressed in mGy·cm. The scanner-derived DLP and the catheterization-derived DAP do not allow comparisons

Fig. 1.2 X-ray protection. Protect both the patient and staff. Use aprons, collars, glasses, curtains, and shields. Distance between X-ray tube and the patient should be maximized keeping the intensifier or flat panel detector as close to the patient as possible. Use the lowest degree of magnification required for accurate interpretation. Remember an adequate use of filters, and the simpler rule than doubling the source-to-operator distance will decrease the operator dose to approximately one quarter. Use the lowest degree of magnification required for accurate interpretation. Minimize radiographic beam time ("cine" acquisition creates 12- to 20-fold higher dose intensities than fluoroscopy mode). Collimation is an efficient radiation-reducing factor. There are less-irradiating angulations: 20° right anterior oblique gets the lowest patient DAP and cranial and caudal angulations raise the doses significantly and are maximum in left lateral angulations

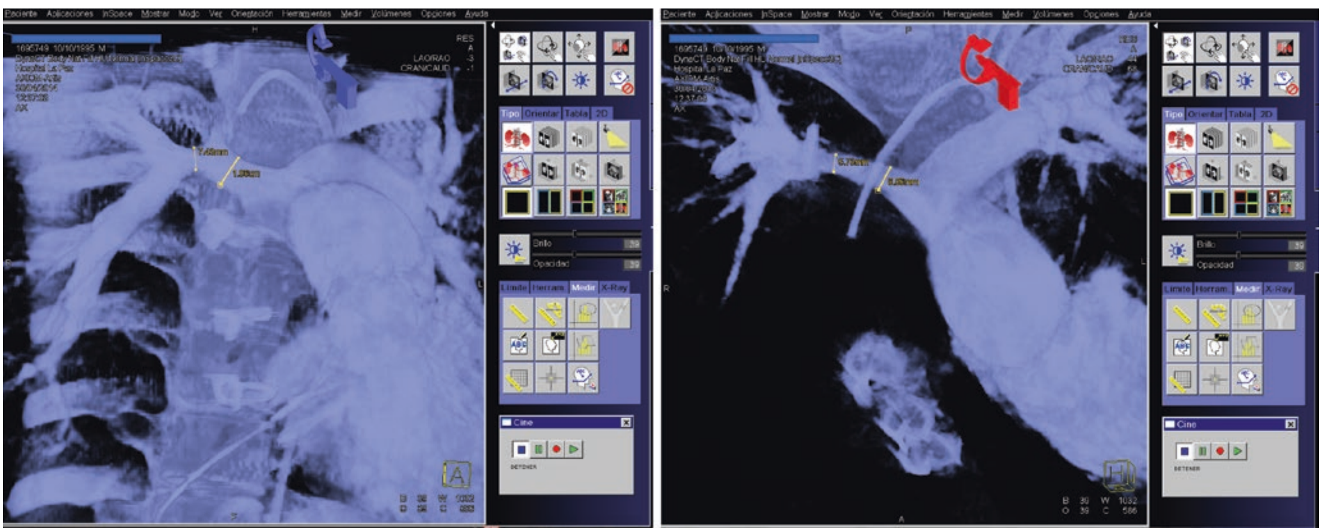


Fig. 1.3 Camera angles. Angiographic computed tomography helps to choose best angles to take measures, but these angles are not always achievable with actual equipment, and alternative angles are necessary. It is worthless to get an angulation such that the image generator position will preclude to work with catheters, sheaths, wires, etc.

Fig. 1.4 Although there is no general agreement, biplane (Fig. 1.4) equipment both reduces total contrast dose (not an insignificant problem) and helps to figure out the area of interest but not always with a significant total X-ray dose reduction

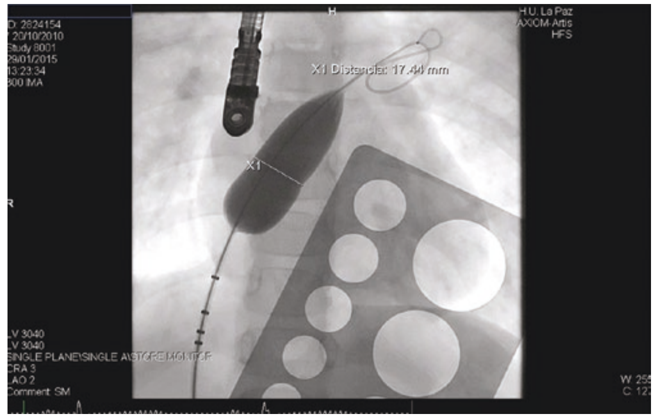
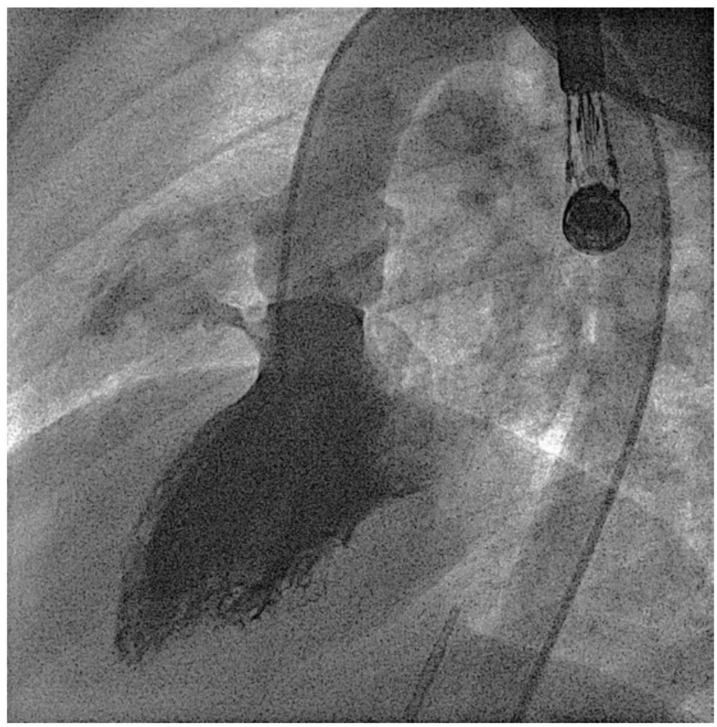


Fig. 1.5 Secundum atrial septal defect. A good profile of sizing balloon can be done in AP projection. A good alternative is a 30° LAO + 30° cranial

Fig. 1.6 Perimembranous septal defect: mid-cranial LAO projection at about 50–60° LAO and as much cranial tilt as the conditions allow are the best. Simultaneous orthogonal RAO if biplane system is available would help to profile the defect. RAO view will outline the high anterior and infundibular (outlet) defects



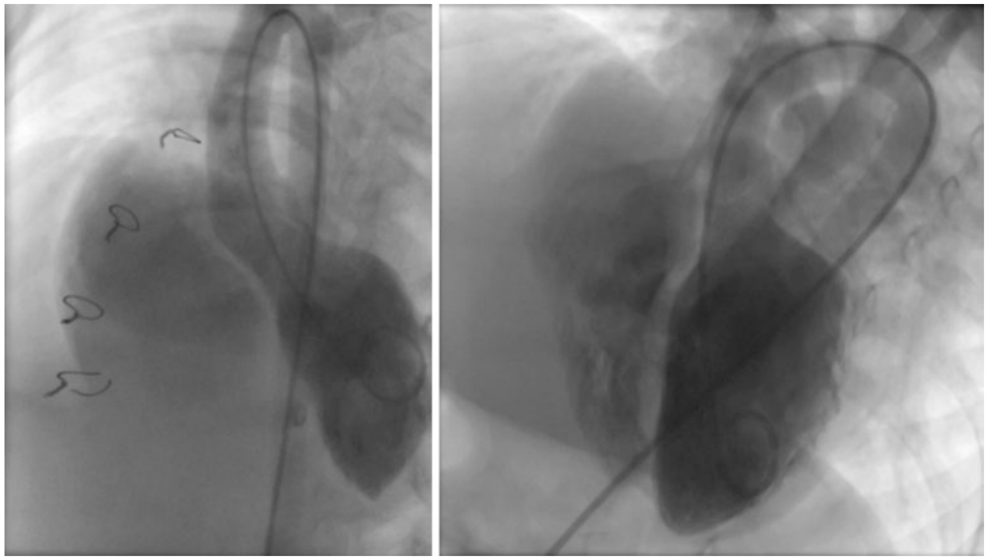


Fig. 1.7 For patients with Gerbode (left), muscular (right), and posterior septal defects, the best option is to begin with a four-chamber view, but more projections could be necessary to profile the defect and to look to more holes

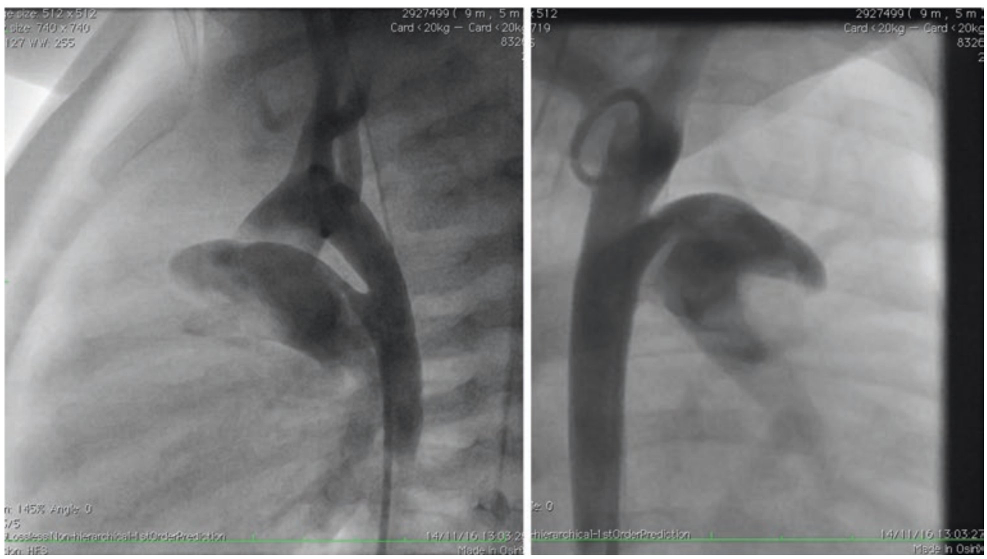


Fig. 1.8 Patent ductus arteriosus. In most of the cases, closure can be straightly performed just with the lateral plane (left). If not well defined, a simultaneous or added shallow RAO will nicely demonstrate the ductus (right). Who ductal arch and aortic arch are overlapped, some caudal tilt on the plane B will help

Fig. 1.9 Modified Blalock-Taussig shunt on the right. A shallow RAO is necessary

Fig. 1.10 Aortic coarctation. PA only is not enough (**a**, **b**), so lateral to best profile the minimum diameter (**c**, **d**) and various degrees of LAO to study transverse arch (**e**) are necessary

Fig. 1.11 Mustard baffle. Superior baffle obstruction is best viewed in 30° LAO, with or without 30° cranial angulation depending on the case. Rotational angiography is an unvaluable help to choose the best projection in this setting

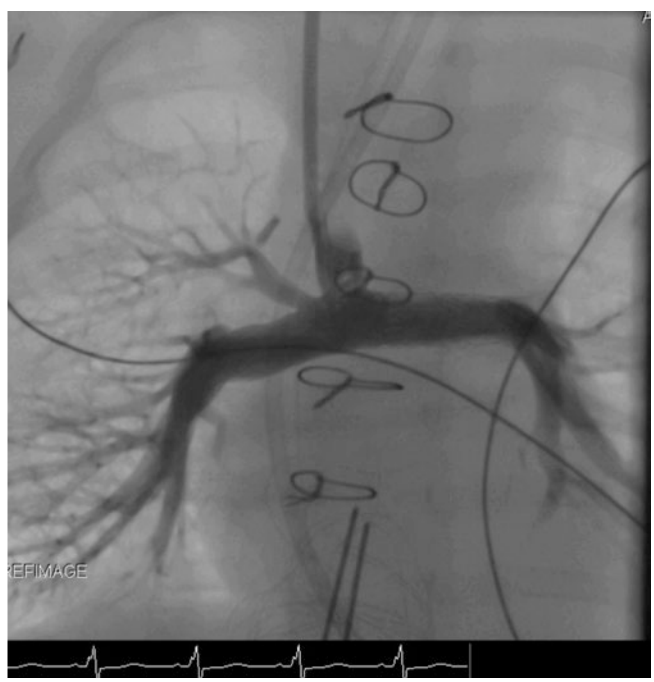


Fig. 1.12 Bidirectional cavopulmonary connection. PA projection does not usually profile anastomosis well, so some degree of caudal (plus or not shallow LAO) should be added

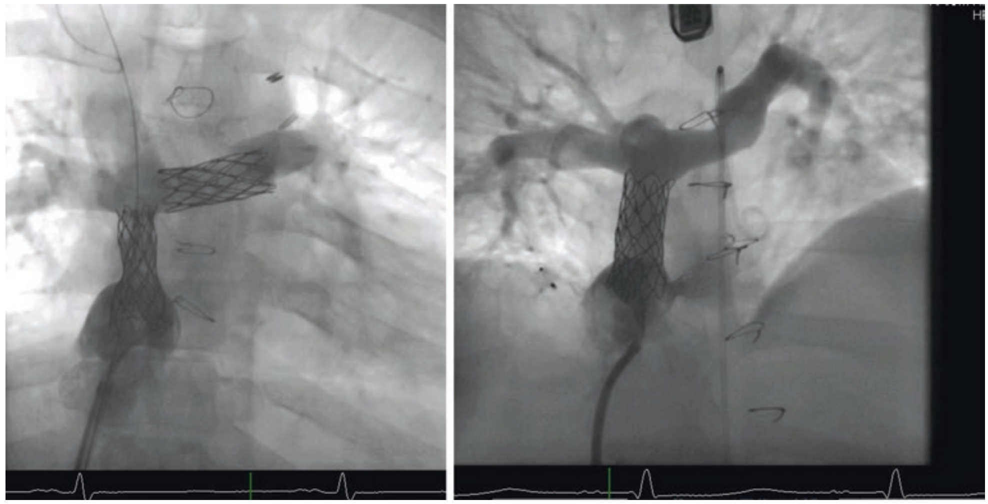


Fig. 1.13 Fontan operation. PA projection is first obtained. Depending of the aim of the study, many particular variations will be needed

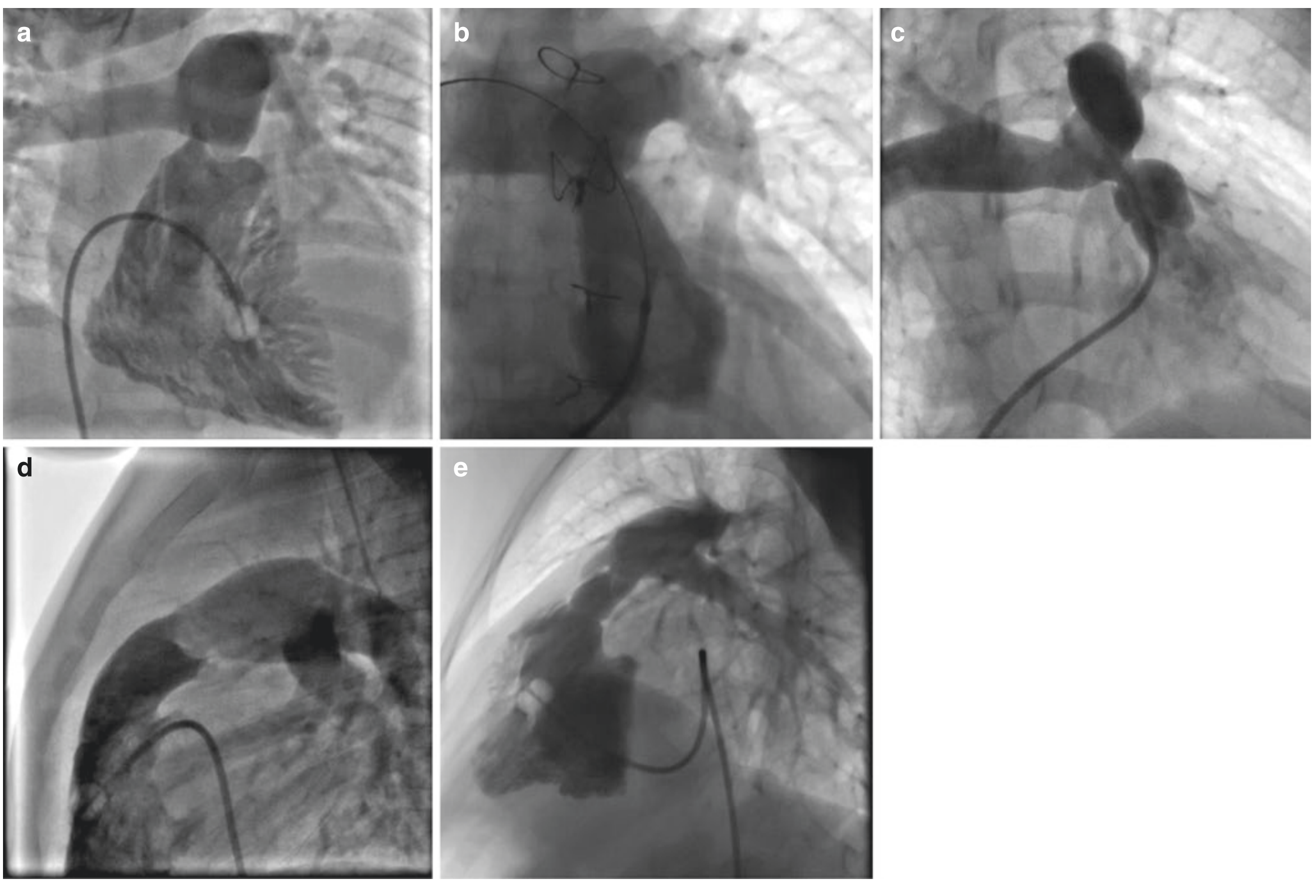


Fig. 1.14 Pulmonary stenosis, pulmonary valve atresia, Fallot's tetralogy, etc. PA projection will produce significant foreshortening (**a**), so some degree of cranial (**b**) and/or OAD (**c**) must be introduced. Best measurements are attained in lateral view (**d**, **e**)

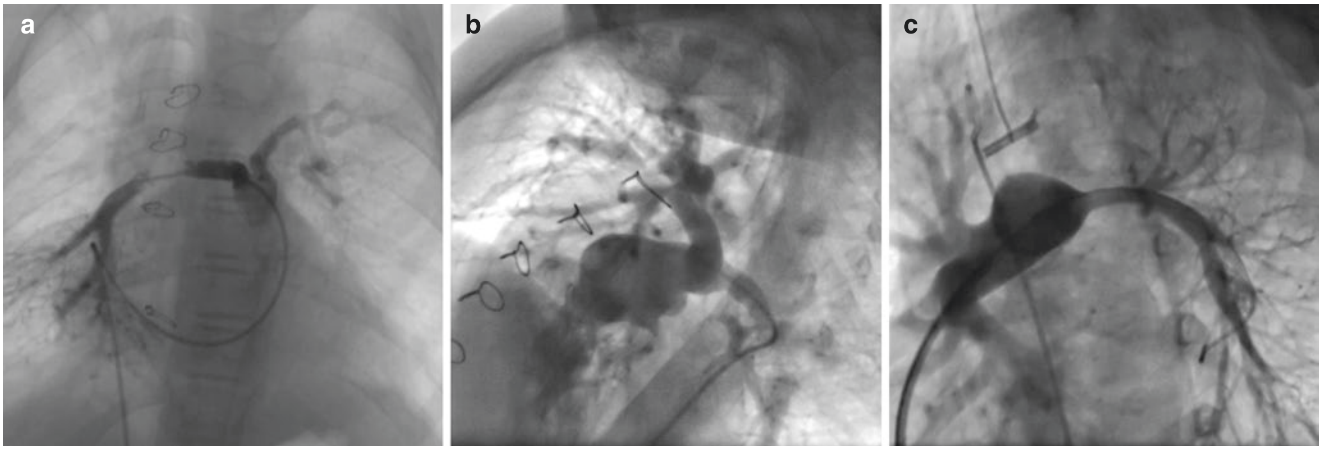


Fig. 1.15 Branch pulmonary stenosis. Rotational angiography is particularly useful (**a**), four-chamber view (40°LAO + 40°cranial) is very useful at the beginning of the study (**b**), as a rule left pulmonary branch is best studied in left oblique projections (**c**), and conversely the right pulmonary artery is best studied in right oblique projections

Table 1.1 Recommended projections in practice in various clinical settings

Projection	Angles, plane A	Angles, plane B
Conventional RAO	40° RAO	
Frontal	0°	
Shallow LAO	1–30°	
Straight LAO	31–60°	
Steep LAO	61–89°	
Left lateral	90° left	
Cranially tilted RAO	30° RAO + 30° cranial	
Cranially tilted frontal (sitting up view)	30–45° cranial	
Cranially tilted shallow LAO	25° LAO + 30° cranial	
Cranially tilted mid-LAO (long axis oblique)	60° LAO + 30–30° cranial	
Cranially tilted steep LAO (hepatoclavicular view)	45–70° LAO + 30° cranial	
Caudally tilted frontal	45° caudal	
AP and lateral	0°	Left lateral
Long axis oblique	30° RAO	60° LAO +20–30° cranial
Hepatoclavicular view	45° LAO + 30° cranial	120° LAO + 15° cranial
Specific lesions	**Angles, plane A**	**Angles, plane B**
Pulmonary stenosis	0° + 30° cranial	Left lateral
RVOT-MPA (sitting up)	10° LAO + 40° cranial	Left lateral
Long axial for LPA biplane	30° RAO	60° LAO + 30° cranial
LPA long axis		60° + 20° cranial
ASD	30° LAO + 30° cranial	
PA bifurcation and branches	30° caudal + 10° RAO	20° caudal
Left ventricular outflow tract obstruction	RAO	Long axis oblique
Aortic coarctation	0°/shallow RAO/shallow LAO	Left lateral/long axis oblique
Ventricular septal defect perimembranous		Long axis oblique
Ventricular septal defect inlet and muscular		Hepatoclavicular view
Ventricular septal defect outlet	RAO	
Patent ductus arteriosus	30° RAO	Left lateral/left lateral + caudal
Mustard superior baffle obstruction	30° LAO + 30° cranial	
Mustard inferior baffle obstruction	Frontal	
Surgical fistula between supraortic arch and branch pulmonary artery	Shallow RAO/LAO	
Fontan operation. Tunnel/conduit obstruction	0°	Left lateral
Fontan operation. Fenestration	Shallow RAO/LAO	

Video 1 Rotational angiography requires particular attention at everything as collision is very easy (MP4 59340 kb)

Video 2 Modern equipment allows to work with 3D images superposed to actual angiography (MP4 16732 kb)

2 Catheters and Wires

Adam Koleśnik and Grażyna Brzezińska-Rajszys

2.1 Diagnostic Catheters

Diagnostic catheters are thin-walled tubes introduced into patient's vessels and the heart via the valved introducer sheaths. Structure of the catheter, its geometry, and other characteristics depend on the purpose it serves. There are many designs and technical solutions created by numerous manufacturers of catheterization equipment. Catheters are named according to their shapes, people who designed them, or the vessels they are supposed to enter. The basic principle of catheter selection, however, is that they must serve the purpose they are suitable for. Thus, in a pediatric cardiac catheterization laboratory, one often uses catheters designed for procedures other than those being performed. Nevertheless, there are some basic catheter categories that the operator has to be familiar with.

2.1.1 Anatomy of the Catheter

Although diagnostic catheters usually look like simple plastic tubes, their construction is quite complex. Materials used should be safe for the patient, assure maneuverability, respond to the torque applied, be kink-resistant, be resistant to the pressures generated during contrast injection, and assure good visibility on fluoroscopy.

Several properties are crucial when selecting a catheter. The outer diameter is traditionally given in French (F), representing outer circumference in millimeters (corresponding to about 0.3 mm of outer diameter), inner lumen diameter in decimal fraction of inch (e.g., 0.035″), length in centimeters, maximal pressure in pounds per square inch (psi), and maximal flow in milliliters per second (mL/s).

There are some discrepancies in describing proximal and distal direction of the catheter. For the purpose of this chapter, the tip of the catheter will be called its distal end and the Luer lock adapter its proximal end.

Catheter manipulation requires application of torque to its part outside the patient. This torque has to be transmitted to the tip. Besides, as mentioned before, the catheter has to be kink-resistant and provide some support while passing through the vessels and/or chambers. This is why shafts of the catheters are usually composed of a plastic material (nylon, polyethylene, polyurethane, PTFE) braided with thin metal meshwork. Depending on the manufacturer, the catheter size and the distal ends of catheters can be made of braided or unbraided material. The tip itself usually lacks reinforcement to assure its softness and minimize the risk of vascular wall injury. The distal tip of the catheter may have an additional radiopaque marker to improve its visualization. Some of the catheters have a single end hole for injection of the contrast medium, for pressure measurements, and for advancing guidewire, while other catheters such as angiographic catheters have multiple side holes for even contrast distribution. It is recommended to avoid any pressure injections of contrast through a catheter with end hole only. Balloon-tip catheters have a CO_2 inflatable balloon at their tips. This balloon is supposed to allow free floating with the bloodstream and prevent tangling between the chordae tendineae in the cardiac chambers. Other catheters have hydrophilic coating that makes them slippery and facilitate their gliding through tortuous vessels. Sizing catheters have additional radiopaque markers embedded in their shafts at known distances, for precise calibration and measurements.

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https://doi.org/10.1007/978-3-319-72443-0_2

2.1.2 Types of the Catheters

2.1.2.1 Angiographic Catheters

The main purpose of the angiographic catheters is the appropriate visualization of anatomy by means of the injection of contrast medium into blood vessels or cardiac chambers. Multiple side holes at the end of the catheter help to distribute the contrast evenly and deliver it efficiently during ventriculography or angiography. End hole allows for over-the-wire insertion of the catheter. The angiographic catheters can withstand high pressure and flow of the contrast medium, without recoil of the catheter during the injection.

There are angiographic catheters of various curves available in the market. Special shapes have been designed for a variety of purposes, e.g., pulmonary angiography. Despite their different shapes and other features, the main principles remain the same.

Berman angiographic catheter is a balloon-tipped catheter without the end hole (Fig. 2.3a). Thus, it cannot be advanced over a guidewire. Since it has a straight tip, the curved wire can be placed inside the catheter to shape it and support it when entering the desired location. The CO_2 inflatable balloon helps to cross the valves with the blood flow. However, in the presence of interatrial or interventricular communications, it can be used to catheterize left heart structures as

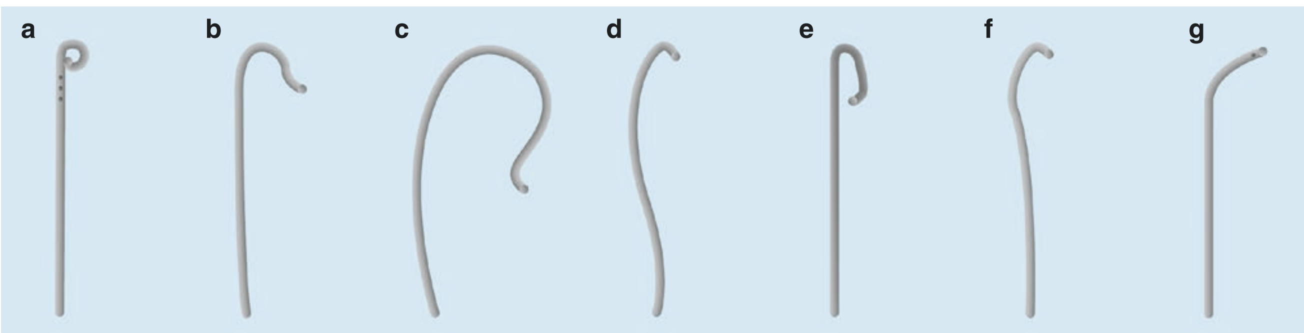

Fig. 2.1 Shapes of selected torque-controlled catheters (see text). (**a**) Pigtail catheter, (**b**) Amplatz left coronary catheter, (**c**) Amplatz right coronary catheter, (**d**) internal mammary catheter, (**e**) Judkins right coronary catheter, (**f**) Judkins left coronary catheter, (**g**) multipurpose catheter

Video 1 Three-dimensional rotational angiography in a patient with tight coarctation of the aorta. The contrast is injected to the left ventricle with the pigtail catheter (see Figs. 2.1a and 2.2). Injection to the ventricle allows for visualization of the aorta and its branches without rapid ventricular pacing, because the contrast mixes in the ventricle and the aorta remains contrasted throughout the injection without any contrast medium washout effect (AVI 1999 kb)

Video 2 Closure of the perimembranous VSD using PFM Nit-Occlud Lê coil. The pigtail catheter is advanced with the guidewire inside. Pigtail catheters are thin-walled especially at their distal ends that makes them soft but susceptible to kinking. Thus, pigtail catheters have to be advanced and withdrawn with the guidewire inside them. While passing through the arterial valves retrogradely, the loop of the guidewire should precede the tip of the catheter to prevent kinking in the valvar sinuses (AVI 4450 kb)

Video 3 Closure of the perimembranous VSD using PFM Nit-Occlud Lê coil. Injection of the contrast medium to the left ventricle in order to assess position of the coil. Side holes are placed proximal to the curved tip. This should be kept in mind when positioning the catheter for contrast infusion or pressure measurement (AVI 1506 kb)

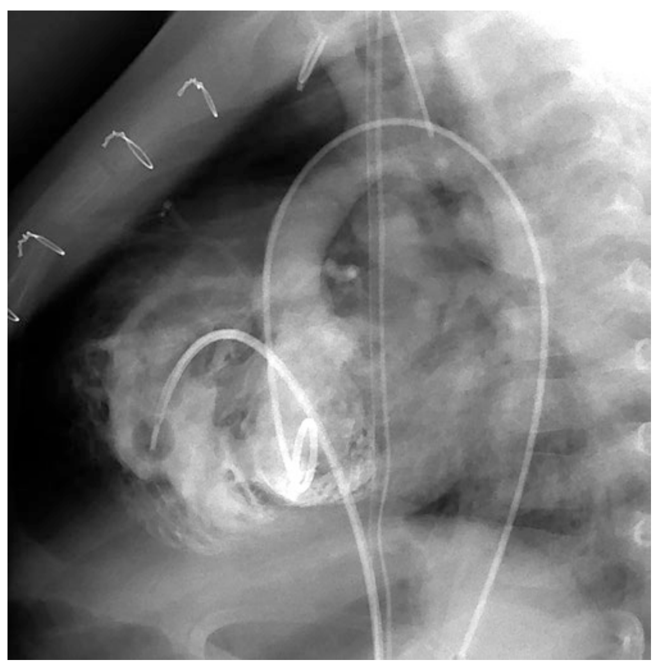

Fig. 2.2 Left ventriculography (retrograde approach) with pigtail catheter—lateral projection. Multiple ventricular septal defects in a 2-year-old patient after pulmonary artery banding and surgical repair of aortic arch hypoplasia and coarctation. Please notice the Berman angiographic catheter with tip balloon inflated with CO_2

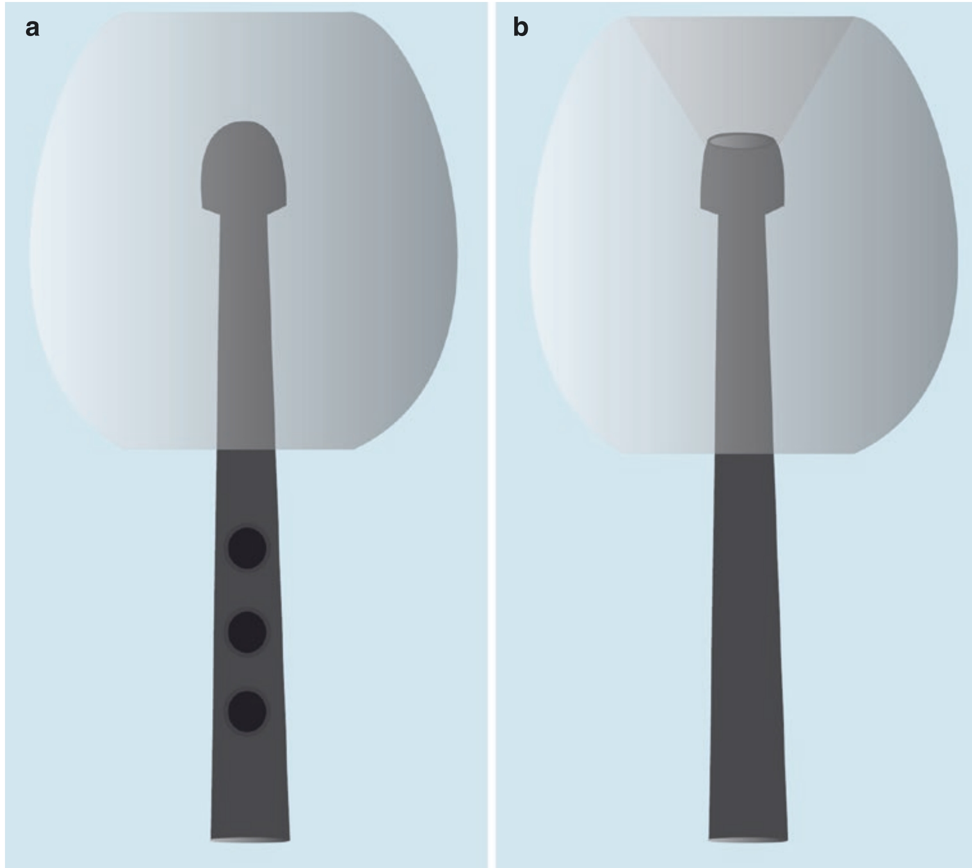

Fig. 2.3 Tips of floating catheters. (**a**) Berman angiographic balloon catheter. (**b**) Pulmonary wedge balloon catheter

Video 4 Three-dimensional rotational angiography. Injection of contrast medium to the right ventricle through the Berman catheter (notice the gas-filled balloon at the tip of the catheter) (AVI 2091 kb)

Video 5 The patient with tricuspid atresia and transposition of the great arteries. The Berman catheter has been advanced to the aorta using the antegrade approach. Balloon at the tip has been inflated with CO_2.The catheter is moving back and forth with the bloodstream (AVI 1598 kb)

Video 6 The patient with tricuspid atresia and transposition of the great arteries (see Video 4). The Berman catheter advanced antegradely through the atrial septal defect to the left atrium, the left ventricle, and the pulmonary trunk. Pulmonary angiography shows banded pulmonary trunk (AVI 2459 kb)

well. Antegrade approach to the aorta is feasible also in patients with transposition of the great arteries, double outlet right ventricle, or functionally univentricular hearts or in the presence of large ventricular septal defects (Fig. 2.4).

Moreover, the balloon catheter can be used to occlude the distal parts of the vessels and perform occlusion arteriography. Balloon occlusion descending aortography helps to force blood flow through aortopulmonary collateral arteries in the tetralogy of Fallot and other congenital cardiac malformations with pulmonary stenosis or atresia (Fig. 2.5).

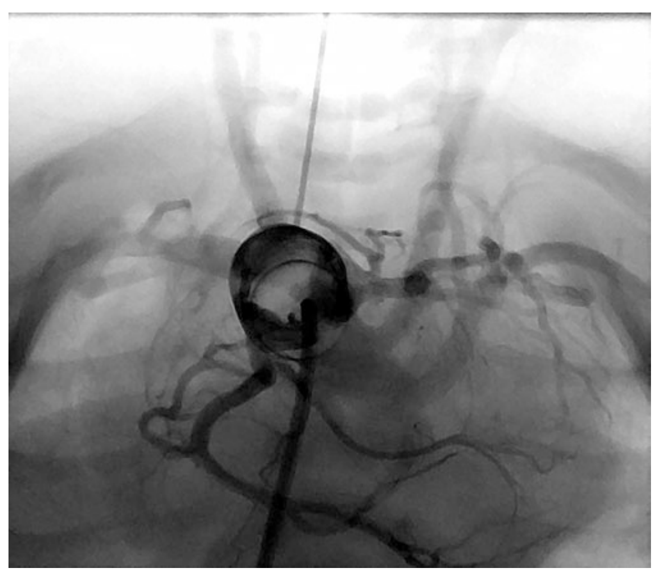

Fig. 2.4 Balloon occlusion ascending aortography (antegrade approach) with Berman angiographic balloon catheter. Antegrade balloon occlusion aortography with 35° caudal angulation is used to visualize coronary arteries in cases of transposition of the great arteries. The angiogram shows origin of the left circumflex artery from the right coronary artery in a 2-day-old patient with transposition of the great arteries

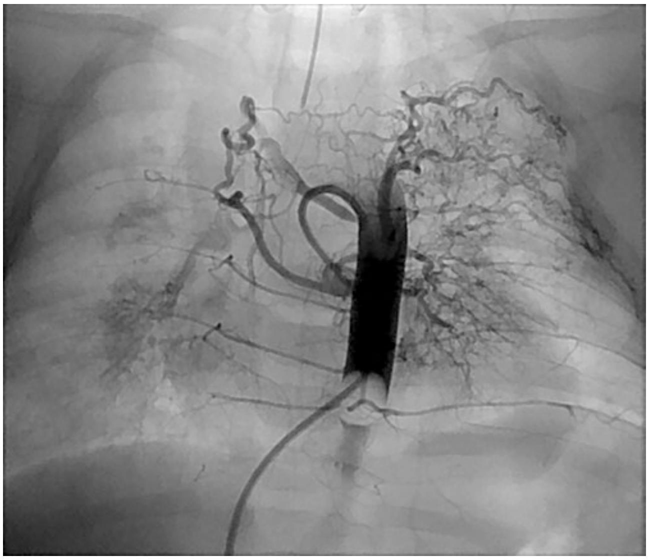

Fig. 2.5 Balloon occlusion descending aortography (antegrade approach) with Berman angiographic catheter—anteroposterior projection. Aortopulmonary collaterals in a 6-month-old patient with double-inlet left ventricle after pulmonary artery banding

Video 7 Balloon occlusion descending aortography in patient with hypoplastic left heart syndrome shows the aortic arch and severely hypoplastic ascending aorta filling retrogradely (AVI 1846 kb)

In fenestrated Fontan patients, one can occlude the fenestration with the balloon tip in order to evaluate changes of blood pressure in the Fontan circulation. All these and many more applications make the Berman angiographic catheter an especially valuable item in the catheterization laboratory inventory.

2.1.2.2 Pulmonary Balloon Wedge Catheters

The pulmonary balloon wedge catheter (Swan-Ganz) is a single end-hole, balloon-tipped catheter, originally invented to measure right heart pressures. Its balloon tip makes it float to the distal pulmonary arteries (Fig. 2.3b). When it reaches the desired position, the inflated balloon occludes the antegrade flow in the vessel. Thus, the pressure in the pulmonary veins and the left atrium can be measured. When placed in the pulmonary vein, one can measure the pressure in the pulmonary arterial bed, based on exactly the same principle as the antegrade pulmonary wedge measurement. However, in the hands of interventional cardiologist, the pulmonary balloon wedge catheter becomes more widely used for advancing the guidewire for interventional procedures, selective pulmonary arteriography, simulation of vessel occlusion, and many others. With the balloon inflated at its tip, it should cross the tricuspid valve safely and minimize the risk of its injury during the following interventions, such as balloon valvuloplasty, pulmonary artery angioplasty, or stent placement. In case of extreme pulmonary artery hypoplasia, injection of the contrast medium through the catheter wedged in the peripheral pulmonary vein with consecutive flush with saline results in retrograde visualization of the pulmonary arterial vessels. Antegrade placement of the Swan-Ganz catheter in the Blalock-Taussig shunt is used, after inflation of the balloon, to simulate the shunt occlusion and monitor pressure changes in the pulmonary arteries. Undoubtedly, the pulmonary wedge catheter should always be available for use in the catheterization laboratory shelf.

2.1.2.3 Curved Catheters

A large variety of curved catheters are designed for selective catheterization of blood vessels. As mentioned before, their names often suggest their particular application. However, the interventionist searching for “right ventricular outflow tract catheter” or “right Blalock-Taussig catheter” would be unsuccessful in finding these. The operator should base selection of the most useful equipment on personal preferences, experience of other specialists, knowledge of catheter properties, and the patient’s anatomy. Most of the curved catheters have a single end hole. They can be used for selective angiography, pressure measurement, and guidewire placement.

Selected curved catheters are presented in Fig. 2.1. Some of these, described below, deserve some more attention.

Coronary catheters are designed to easily intubate the normal coronary arteries. Judkins and Amplatz catheters are the most popular (Fig. 2.1b–e). Among them, Judkins right coronary catheter (JR) is one of the most widely used in the cardiac catheterization laboratory. The distal part of the catheter is gently rotated to find support in the ascending aorta, and the tip bends at almost a right angle to reach the orifice of the right coronary artery.

In pediatric catheterization laboratory, this shape has proved to be useful in the selective catheterization of Blalock-Taussig shunts and collateral vessels, entering the right ventricle outflow tract, and many other procedures (Fig. 2.6).

Video 8 Right coronary artery angiography in transplanted heart. Judkins right coronary catheter, 30° right anterior view. Please notice an abnormal collateral vessel between the right conal branch and the right pulmonary artery (AVI 738 kb)

Video 9 Hand injection of contrast medium to a major aortopulmonary collateral artery in a patient with pulmonary atresia and intact interventricular septum. The artery was engaged with Judkins right coronary catheter (AVI 1758 kb)

Video 10 Judkins right coronary catheter advanced to right ventricle outflow tract through the femoral venous access in a patient with pulmonary atresia and intact interventricular septum undergoing radiofrequency perforation of atretic pulmonary valve. Multipurpose catheter has been simultaneously inserted to the pulmonary trunk via ductus arteriosus using femoral arterial approach (AVI 778 kb)

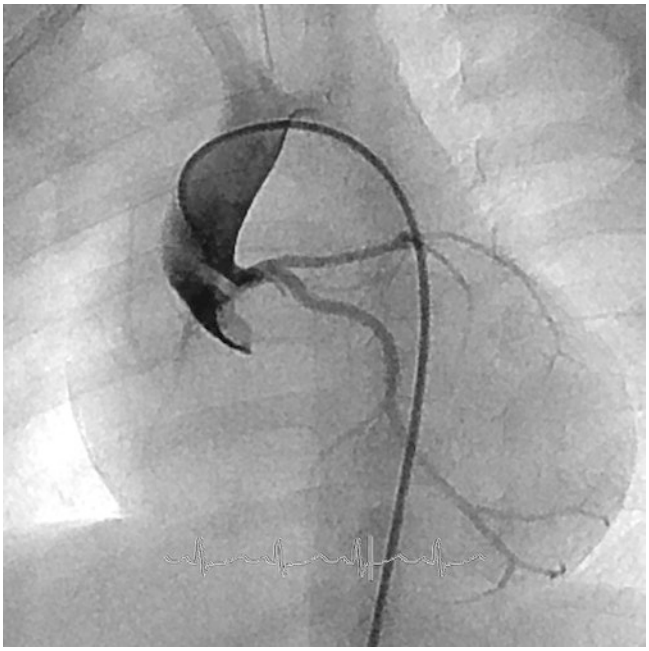

Fig. 2.6 Ascending aortography (retrograde approach) with Judkins right coronary catheter—left anterior oblique projection. Catheter positioned in front of the opening of critically stenosed aortic valve in a 3-day-old patient allowing for easy insertion of the guidewire to the left ventricle and balloon valvuloplasty

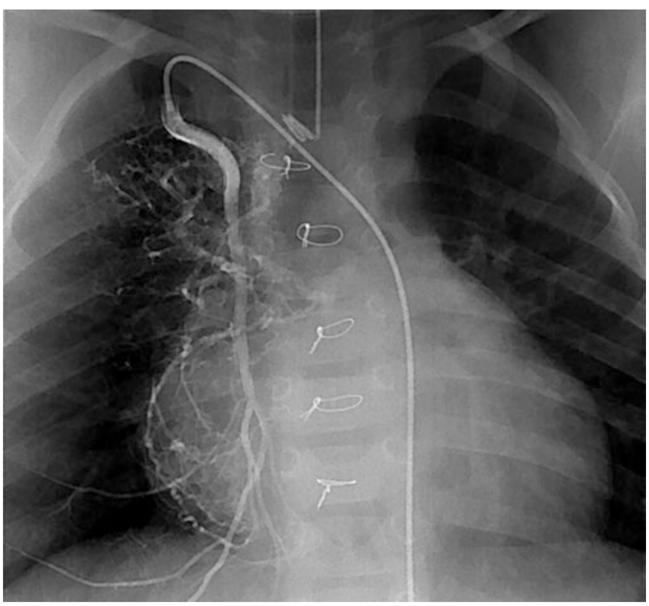

Fig. 2.7 Selective angiography of the right internal thoracic artery (posterior-anterior projection) with right internal mammary catheter. Small systemic-to-pulmonary collaterals in a 2-year-old patient with hypoplastic left heart syndrome after Norwood-Sano operation

Video 11 Right internal thoracic artery angiography done using multipurpose catheter advanced antegradely over the hydrophilic guidewire in patient after Norwood-Sano procedure for hypoplastic left heart syndrome. Dilated internal thoracic artery provides collateral inflow to the right pulmonary artery (AVI 565 kb)

Other applications of Judkins right coronary catheter include crossing restrictive interatrial communications (especially in hypoplastic left heart syndrome patients), crossing interventricular septal defects, and many others.

Internal mammary catheters with their C-shaped tips can be used to enter vessels having origins at acute angles. Their applications include selective catheterization of Blalock-Taussig shunts and collateral vessels (Fig. 2.7).

Multipurpose (MP) catheters have their distal ends curved at an obtuse angle (Fig. 2.1g). Usually there is at least one side hole near the tip. Such catheters, in accord with their name, can serve multiple purposes such as angiography, pressure measurement, and selective catheterization. They can be used to cross a tight coarctation, enter the branches of the aortic arch, reach the left atrium from the femoral vein and the right atrium, and place the guidewire in the pulmonary vein before atrial septal defect device closure.

2.1.2.4 Special Catheter Types

The Multi-Track angiographic catheter (NuMED) has a short lumen for the guidewire at its tip. Thus, the tip can be introduced over the wire to a desired location, while the shaft remains free and multiple side holes remain open for use. This allows injection of contrast medium for angiography and measurement of pressures without losing the position of the guidewire.

Microcatheters are superthin catheters that can be introduced through standard lumen (0.035″–0.038″) single end-hole catheters for selective catheterization of small-sized vessels. Once the vessel is catheterized, one can deliver a microcoil through the guidewire lumen to occlude it. In pediatric and congenital cardiology practice, closure of small collateral vessels appears to be the major indication.

Guiding catheters are single end-hole angled catheters in shapes similar to diagnostic catheters, but with much larger lumen, which permits advancement of interventional equipment. They are widely used in coronary interventions to introduce rapid exchange balloon catheters with a side hole for the guidewire. The walls of the guiding catheters usually possess a three-laminar structure with metal braiding in the middle layer. The size of the guiding catheter, given in French, reflects its outer circumference (as opposed to the introducer sheaths sized by their lumen circumference). In congenital heart disease patients, application of guiding catheters is limited.

2.1.3 Selection of the Catheter and Catheter Manipulation

Every operator has own experience-based preferences. Nevertheless, some points need to be considered. First of all, the goal of the procedure has to be specified. For example, in the right heart, during catheterization for idiopathic pulmonary hypertension where angiography is not a standard component, the pulmonary wedge catheter is an obvious choice. Should right ventriculography or pulmonary angiography be planned, the Berman floating angiography catheter or multipurpose catheter is a reasonable choice. Also the size of the catheter should match the objectives, because it determines the maximum flow and contrast injection pressure. In case the diagnostic catheterization is followed by the intervention, one has to check if the inner lumen can accept the appropriate guidewire or the device. Length is another parameter worth considering. It can be really annoying when after long time of manipulation the catheter is too short to reach its destination.

With all kinds of catheters, it is important to remember the anatomic details, find support sites for the catheter tip and the shaft, and consider the use of a guidewire to position a catheter or to shape it. Wherever possible, biplane fluoroscopy should be used during the procedure. Manipulation principles are different for floating catheters and torque-controlled catheters. Some guidelines and tips and tricks are presented below.

2.1.3.1 Floating Catheters

Floating catheters (Berman, Swan-Ganz) are very soft, and their response to torque is limited. They should float freely in the direction of the blood flow. Nevertheless, especially in difficult anatomy or valvar insufficiency, it may be difficult to manipulate them. Additionally, floating catheters are packaged in a curved manner, and it may be impossible to straighten them completely. The problem can start just after crossing the introducer sheath. Without the balloon inflated, they can enter side branches. Inflation of the balloon makes the catheter float to the right atrium. Once the right atrium has been reached, it is possible to enter the superior vena cava. Sometimes it is possible to direct the tip posteriorly with a gentle torque and push the catheter up to the superior vena cava. In case of failure, insertion of a straight guidewire may solve the problem. Without a guidewire inside and without the balloon inflated, the catheter is likely to enter the left atrium via an atrial septal defect or patent foramen ovale, if present. To enter the left pulmonary veins, the catheter should be directed posteriorly. Otherwise, it will enter the left atrial appendage. Inflation of the balloon of catheter placed in the left atrium, close to the interatrial septum followed by a clockwise torque, may help to cross the mitral valve and enter the left ventricle. If this maneuver does not work, one can use the stiff end of the guidewire bent in a U-shape to angle the distal end of the catheter. Guidewire will also help to transmit the torque. In the left ventricle, the catheter will float toward the apex. Again, a curved stiff end of the guidewire may help to bend the catheter (with the balloon inflated) toward the interventricular septum and push it up into the aorta. To avoid the tension onto the ventricular wall, the guidewire should be partly withdrawn from the catheter, to permit free floatation of the balloon.

In most of the cases, the catheter floats from the right atrium to the right ventricle. If this does not happen, an angled guidewire tip may be helpful to curve the catheter. Another solution is to find support for the catheter tip in the atrial wall, push it further to the atrium to make it bend, and then pull it back. The catheter should recoil and jump into the ventricle. The third method is to create a loop in the right atrium by pushing the catheter with some clockwise torque. Once the loop has been created, the catheter may enter the right ventricle and float to the outflow tract. The atrial loop can also be helpful to reach the right ventricular outflow tract, when the catheter keeps floating toward the ventricular apex. If it is stuck at the apex, a coiled guidewire can help to free it. Shaping the catheter with a guidewire is also useful to manipulate into the branch pulmonary arteries.

There are some issues to be kept in mind:

1. The balloon is able to accommodate more CO_2 than just one syringe; the more the balloon is inflated, the easier the floating is, but caution is needed as the balloon can rupture with too much CO_2.
2. The catheter can be straightened or bent using the guidewire; the guidewire helps to transmit the torque.
3. Creating a loop can help to manipulate with the catheter; it is better to straighten the catheter as soon as its final destination has been reached.
4. Especially in blood vessels, the balloon can obstruct them and alter the blood pressure; it should be deflated during measurements of pressure.
5. In selected applications, obstruction of the vessel with the balloon tip can help to make a selective contrast injection or perform an occlusion test; always remember where the hole(s) is(are).
6. When performing balloon occlusion angiography, the vessel occlusion time should be kept to a minimum; after inflation of the balloon, the catheter will float downstream—pull it back to the desired position, and deflate the balloon as soon as the angiography has been performed.

2.1.3.2 Torque-Controlled Catheters

Most of the catheters are torque-controlled. The torque is applied by the operator at the proximal end of the catheter.

Most of catheter tips lack braiding. That makes them soft and susceptible to kinking. While crossing the blood vessels, angled tips may tend to enter side branches/tributaries. If this problem occurs, they should be introduced over a guidewire. This is mandatory for pigtail catheters. Applications of selected catheters have been discussed already.

The importance of selection of an appropriate catheter shape is undisputed. Sometimes the shape has to be modified to reach a desired location. One can use a guidewire to make the angled catheter straight. On the other hand, the stiff end of a guidewire can be used to apply additional curvature. Entering the right ventricular outflow tract with the Judkins right coronary catheter is a good example. The catheter introduced to the right atrium will tend to move to the superior atrial wall, the right atrial appendage, the superior vena cava, or the left atrium through the atrial septal defect. One can, however, bend the catheter with an angled guidewire and then withdraw it to allow entry into the right ventricle. Torque applied to the catheter will direct the tip to the outflow tract. Should a new shape be permanent, one can reshape it by placing the catheter in hot water or in steam with a stiff, pre-shaped guidewire inside. When the new shape is achieved, the catheter has to be cooled in saline.

Sometimes it is relatively easy to enter an origin of the blood vessel, but the guidewire makes the catheter recoil instead of entering the vessel. This may happen in major aortopulmonary collateral arteries and Blalock-Taussig shunts. If the catheter shaft is pushed excessively, an angle between the shaft and the tip inside the vessel may become too acute. Under such conditions, the guidewire tip is unable to straighten the catheter tip, it pushes the catheter further, and the tip recoils. Hence, it is better to straighten the angle by pulling the catheter down.

2.2 Guidewires

There are plenty of guidewire types and designs used in cardiac catheterization laboratory, produced by numerous manufacturers. Spring guidewires are composed of inner core made of stainless steel or nitinol, accompanied by a fine, steel safety wire and outer fine steel winding. Most of spring wires are coated with polytetrafluoroethylene and sometimes heparin to prevent clotting. In the distal part of the guidewire the core narrows or there is just a safety wire and outer winding. It makes the tip soft and limits a risk of injury to vascular or cardiac wall. The soft tip can adapt to a vessel shape, cross stenotic areas, and tortuosities. Wires with "floppy" tips can be especially useful in such setting. Tips of guidewires are straight or curved. J-tips are the most frequently found. The stiffer the wire is, the more support it provides to diagnostic or therapeutic catheters. Guidewires with a core wire extending from the proximal to distal end can transmit the torque 1:1 or near to it, which makes them more maneuverable. Tips commonly have platinum, gold, or tungsten elements to make them more radiopaque. Also guidewire shafts can be coated with, e.g., polyethylene/tungsten material, to enhance their visibility on fluoroscopy.

Video 12 The perimembranous ventricular septal defect is crossed with the hydrophilic guidewire. The Judkins right coronary catheter remains in the ascending aorta, while the guidewire is advanced alone through the aortic valve and the ventricular septal defect (AVI 4456 kb)

Video 13 Patient after Norwood-Sano procedure for hypoplastic left heart syndrome. Three-dimensional road map based on 3D rotational angiography (the contrast medium has been injected to the right ventricle). Multipurpose catheter and hydrophilic guidewire are used to engage the Sano conduit (AVI 7318 kb)

Guidewires with hydrophilic coating are slippery when wet. They glide through tortuous vessels easily. It can be difficult to manipulate them, so a special plastic torque device is very useful. Hydrophilic wires have to be wet all the time, because they become sticky when dried.

Steerable guidewires have an additional filament attached to a proximal handle. An operator can change the shape of their tip by moving the handle. Thanks to the nitinol core, the tip returns to its initial shape. Such guidewires are used to navigate through tortuous vessels or cross the stents without passing between the struts.

Pressure wires are equipped with a pressure transducer at their tip. Initially, pressure wires were designed to measure pressure gradients across stenotic coronary arteries to assess fractional flow reserve. Gradually, other applications were developed, e.g., measurement of pressure gradients through stenotic valves or vessels such as banded pulmonary arteries in patients after hybrid procedures for hypoplastic left heart syndrome.

Size of a guidewire is given in fraction of inch. The length is measured in centimeters. Especially long (260–300 cm) exchange wires are used to exchange long catheters. Some guidewires can be additionally extended using extension wires.

Guidewires are used to guide diagnostic catheters, therapeutic catheters, guiding catheters, and introducer sheaths through the heart or the blood vessels. Selection of the guidewire has to match the purpose of its usage. One has to consider:

1. Diameter of the guidewire: the operator should know what size the catheter is able to accommodate. Generally, back-bleed ports with flush port should be used to prevent bleeding and formation of thrombi. It becomes especially important in huge catheter lumen/guidewire disproportion, since the bleeding can be significant. In case a flush port is not available, one has to remember to rinse the

wire with heparinized saline frequently. If the intervention is needed, the size of the wire has to be chosen according to the lumen of interventional equipment, e.g., a balloon catheter.

2. Length of the guidewire: when it is too short, it will not leave the catheter tip or may be unable to reach a desired position. It can also be impossible to exchange catheter over the wire. As mentioned before, some guidewires can be extended if needed.
3. Hydrophilic coating: it helps to cross tortuous vessels and narrow stenoses. In spite of softness of hydrophilic catheter tip, it can easily perforate the heart or vessel wall, especially while exiting the catheter. That is why rather standard guidewires and not hydrophilic nor thin coronary wires are recommended to cross a critically stenotic aortic valve. The latter are more likely to perforate valvar leaflets.
4. Length of a soft tip: long, soft tips can enter the planned location but appear too extensive to support interventional equipment. On the other hand, guidewires with short tips are more traumatic.
5. Stiffness: it is safer and easier to advance catheters or sheaths using a stiff wire because of the better support. Softer wires can kink and lose their position or just make advancement of equipment impossible.
6. Shape of a tip: J-tipped guidewires are considered to advance more easily without entering side branches or tributaries. Nevertheless, the vessel diameter has to be large enough to accommodate the tip. Curved tips of some guidewires help to manipulate with the torque to reach a chosen location. Steel-core wire tips can be formed by an operator to get the best shape she/he needs.
7. Torque transmission: wires with a core continuous from proximal to distal end transmit the torque better than those lacking the core at their tips. The longer the floppy tip is, the more is the torque transmission limited.
8. Trackability and steerability: the shaft of the wire should be able to follow its tip through the tortuosities or narrowings in accord with operator's maneuvers.

Video 14 A 13-year-old patient with calcified and stenotic aortic homograft in the pulmonary position (primarily pulmonary stenosis with dysplastic pulmonary valve replaced with Contegra followed by pulmonary homograft and, finally, aortic homograft). Balloon interrogation test to check the proximity of coronary arteries. The balloon catheter (BiB, NuMED) has been advanced to the graft over extra-stiff Lunderquist guidewire through 12F Mullins long sheath and inflated. At the same time, 3D rotational aortography has been performed to visualize coronary arteries (AVI 2111 kb)

As described in the section about catheter manipulation, stiff proximal end of a guidewire can be used to bend or shape catheter tips. One has to be cautious to not exit the catheter with a stiff end of the wire, as it can damage or perforate vascular structures or walls of cardiac chambers.

2.3 Introducer Sheaths

Introducer sheaths are used to assure safe vascular access, allow the insertion of catheters and interventional equipment, and help to guide the devices through tortuosities of the cardiovascular system. The sheaths are usually equipped with a back-bleed valve to prevent an excessive blood loss and a side port for flushing, pressure measurements, and, occasionally, contrast infusion.

The sheath is a thin-walled plastic tube composed of the material rigid enough to prevent kinking in the blood vessels. Their size reflects the inner diameter of the tube, i.e., the diameter of the dilator used to allow the smooth passage through the vascular wall. Thus, four French introducer sheaths can accommodate four French catheters. The outer dimension of the sheath is wider and depends on the thickness of the material the tube is made of. Dilators have a long, tapered tip sticking out of the sheath. The dilator and sheath locked together are introduced to a blood vessel over the wire. Size of the dilator inner lumen should be known to the operator, especially in case there is a need to exchange the sheath and use the one of the other size.

Short introducer sheaths are used to maintain the vascular access and manipulate with the equipment. Their length should match the anatomy of the vessels—the sheath should not end opposite to a vascular wall, since it can produce complications such as vascular wall injury and bleeding. Long sheaths are used to straighten blood vessels and create a smooth tunnel for diagnostic and, especially, interventional equipment, such as stents, occluders, vascular plugs, biopsy forceps, or transseptal needles. Most of them can be recurved using hot steam or air to meet the needs of particular procedures. Mullins sheath is a long, curved sheath with multiple diagnostic and interventional applications. High flexibility and the ability to pass through especially tortuous vessel without kinking or collapsing are the features of long Flexor introducer sheath. Details of long sheath usage are presented in chapters devoted to specific procedures.

Back-bleed valves and side ports can be an integral part of the introducer sheath or be separate devices attached to the

Luer lock at the end of the sheath. Usually, the back-bleed valve incorporated into the sheath is a latex diaphragm with a hole that permits insertion of the equipment. Resistance of such valve can significantly influence the effectiveness of manipulation and transmission of the torque applied to catheters and wires. In case of some introducer sheaths, the structure and rigidity of their valves make the effective manipulations impossible. The valves with a screw-tightened hub (Tuohy type) can be regulated according to the needs of the operator. Detachable back-bleed valves with side ports can also be removed once the device is in the sheath and obturates its lumen, so that the control over the equipment is easier and more effective.

Video 15 Prestenting of the calcified aortic homograft prior to implantation of the Melody percutaneous pulmonary valve. The covered CP stent crimped on 18 mm BiB balloon is advanced over the Lunderquist guidewire through 12F Mullins sheath. Notice two kinks of the sheath the stent has to pass (AVI 4461 kb)

Video 16 Percutaneous closure of the perimembranous ventricular septal defect. Kink-resistant Flexor sheath is advanced using “kissing” technique over the guidewire arteriovenous loop (AVI 4456 kb)

3 Balloons

Caroline Ovaert and Duarte Martins

3.1 Introduction

Balloons are generally used for direct dilation of vessels or stents. Specific balloons may be used for other purposes, such as atrial septostomy, sizing of defects, temporary occlusion of shunts or collateral vessels in order to stabilize occlusion devices or to perform hemodynamic assessments.

Balloons are currently available in various lengths and diameters and differ with regard to pressure characteristics, compliance, profile, balloon morphology and inner lumen diameter (Table 3.1). A broad spectrum of balloon catheters must be available in each catheterization laboratory when performing procedures in patients with congenital heart defects, in order to be able to adapt to different weights, anatomies and procedures.

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