

Cardiac Catheterization and Angiography

Edited by WILLIAM GROSSMAN, M.D.

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THIRD EDITION



LEA & FEBIGER PHILADELPHIA
1986



LEA & FEBIGER
600 Washington Sq.
Philadelphia, Pa. 19106-4198
U.S.A.

Library of Congress Cataloging in Publication Data

Main entry under title:

Cardiac catheterization and angiography.

Includes bibliographies and index.

1. Cardiac catheterization. 2. Angiography.

I. Grossman, William, 1940- [DNLM:

1. Angiocardiography. 2. Heart Catheterization.

WG141.5.C2 C267]

RC683.5.C25C37 1985

616.1'207575

85-4545

ISBN 0-8121-0994-5

First Edition, 1974

Second Edition, 1980

Reprinted, 1985

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PRINTED IN THE UNITED STATES OF AMERICA

Print number 3 2 1

Preface

THIS textbook in both its conception and design is aimed at the instruction of physicians training to become cardiologists. The intent was to compile a book that would be practical and that would bring together clear and concise descriptions of the major techniques currently employed in cardiac catheterization and angiography. No effort was made to be exhaustive or to construct a compendium of every technique that has been reported; instead, we have concentrated on the detailed description of a few methods that are moderately successful, that are practical, and whose strengths and weaknesses are well known.

The book begins with a section on general principles of cardiac catheterization and angiography. This has been substantially revised from the second edition, and contains information on proper utilization of radiologic and cineangiographic equipment and the incidence, causes, and prevention of complications of cardiac catheterization.

The second section deals with techniques of catheter placement, including discussions of arteriotomy, percutaneous catheterization, transseptal catheterization, balloon-tipped flow-directed catheters, and special considerations in the catheterization of infants and children. Subsequent sections on hemodynamic principles and angiographic techniques attempt to cover basic knowledge in these areas, with an emphasis on practical application and on avoidance of commonly encountered mistakes and pitfalls.

Discussion of the interpretation of hemodynamic and angiographic findings has been largely separated from the description of techniques. Interpretation is discussed and illustrated at the end of the book in the chapters on profiles of characteristic hemodynamic and angiographic abnormalities in specific disorders (Part VI). This separation is purposeful, and serves to emphasize the importance of considering hemodynamic and angiographic data together when analyzing the physiologic and anatomic abnormalities presented by a given disorder.

A unique section on "Evaluation of Cardiac Function" offers pragmatic discussions of recent advances and the current state of the art in evaluation of systolic and diastolic ventricular function, atrial pacing, ventricular volume analysis, myocardial blood flow, dynamic and isometric exercise, and electrophysiologic techniques.

In the third edition, the section on "Special Catheter Techniques" (Part VII) has been greatly expanded and now contains chapters on coronary angioplasty, percutaneous placement of intraaortic balloon pump, endomyocardial biopsy, placement of temporary and permanent pacemakers, and application of lasers and coronary angioscopy in the cardiac catheterization laboratory. These chapters reflect many of the exciting developments in cardiology in recent years, and give practical instruction aimed at assisting the cardiologist and cardiology trainee in the application of these advances to clinical practice.

This book could not have been written without the help of many individuals whose names do not appear in the list of contributors. In particular, I am grateful to Dr. Eugene Braunwald; my many colleagues in the Departments of Medicine at Harvard Medical School and the Beth Israel and Brigham and Women's Hospitals, who gave me encouragement and advice; to our Cardiology Fellows whose thoughtful questions and comments stimulated me to undertake this task in the first instance; and to the technicians and staff of our laboratory whose hard work and dedication allow the precepts of this book to be transformed into action each day.

I hope that this book will be of value not only to those involved in the daily practice of cardiac catheterization and angiography but to all who are involved in the care of patients with serious heart disease. Most of all, I sincerely hope that the lessons of this book will benefit the patients themselves; without this final result, it will have been a sterile venture.

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PART I

*General Principles of Cardiac
Catheterization and Angiography*

chapter one

Cardiac Catheterization: Historical Perspective and Present Practice

WILLIAM GROSSMAN

IT IS difficult to imagine what our concepts of heart disease might be like today if we had to construct them without the enormous reservoir of physiologic and anatomic knowledge derived during the past 30 years in the cardiac catheterization laboratory. As Andre Cournand remarked in his Nobel Lecture of December 11, 1956: "the cardiac catheter was . . . the key in the lock."¹ By turning this key, Cournand and his colleagues led us into a new era in the understanding of normal and disordered cardiac function in man.

HISTORICAL REVIEW

According to Cournand,² cardiac catheterization was first performed (and so named) by Claude Bernard in 1844. The subject was a horse, and both the right and left ventricles were entered by a retrograde approach from the jugular vein and carotid artery. An era of investigation of cardiovascular physiology in animals then followed, resulting in the development of many important techniques and principles (pressure manometry, the Fick cardiac output method), which awaited direct application to the patient with heart disease.

Although others had previously passed catheters into the great veins, Werner

Forssmann is generally credited with being the first person to pass a catheter into the heart of a living person—himself.³ At age 25, while receiving clinical instruction in surgery at Eberswalde, near Berlin, he passed a catheter 65 cm through one of his left antecubital veins, guiding it by fluoroscopy (he looked through a mirror held by his nurse in front of the fluoroscope screen) until it entered his right atrium. He then walked to the Radiology Department (which was on a different level, requiring that he climb stairs), where the catheter position was documented by a chest roentgenogram (Fig. 1-1). During the next two years, Forssmann continued to perform catheterization studies, including six additional attempts to catheterize himself. Bitter criticism, based on an unsubstantiated belief in the danger of his experiments, caused Forssmann to turn his attention to other concerns, and he eventually pursued a career as a urologist.

It is of interest that Forssmann's primary goal in his catheterization studies was to develop a therapeutic technique for the direct delivery of drugs into the heart. He wrote: "If cardiac action ceases suddenly, as is seen in acute shock or in heart disease, or during anesthesia or poisoning, one is forced to deliver drugs locally. In such cases the intracardiac injection of drugs may be life saving. However, this may be a dangerous pro-

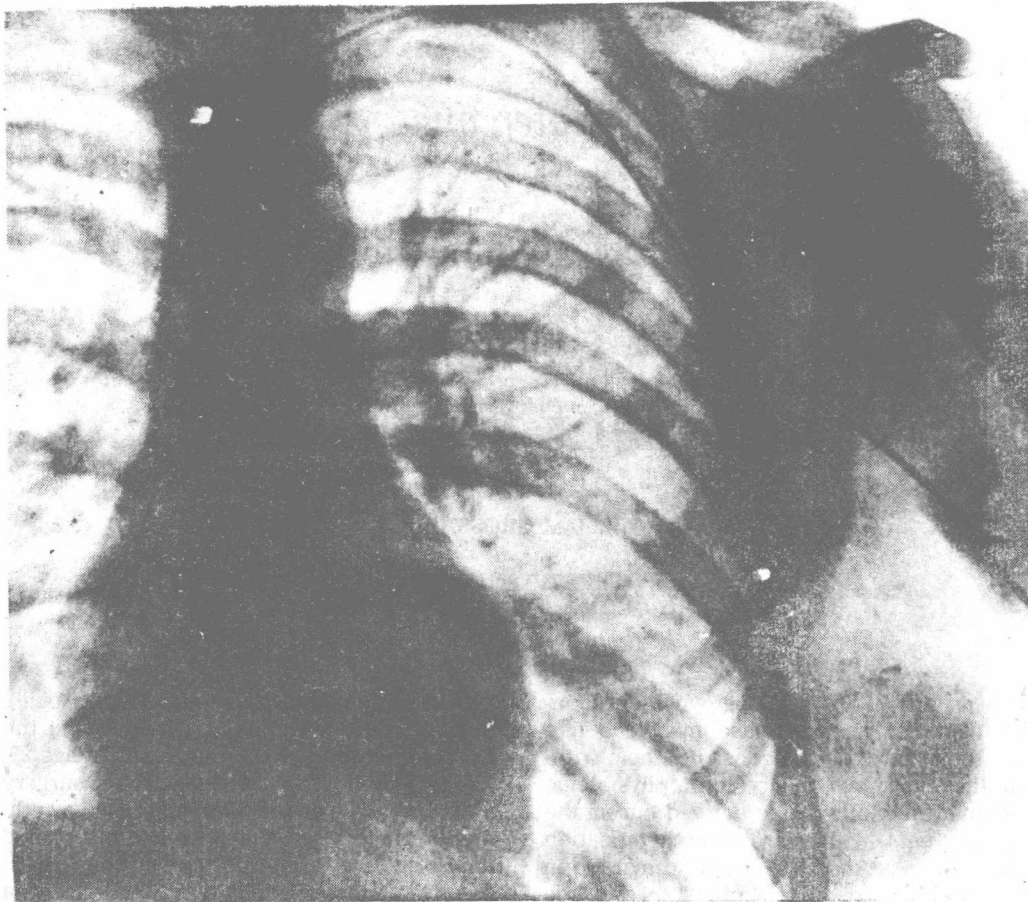


Fig. 1-1 The first documented cardiac catheterization. At age 25, while receiving clinical instruction in surgery at Eberswalde, Werner Forssmann passed a catheter 65 mm through one of his left antecubital veins until its tip entered the right atrium. He then walked to the Radiology Department, where this roentgenogram was taken.² (Klin Wochenschr 8:2085, 1929. © Springer-Verlag Berlin, Heidelberg, New York)

cedure because of many incidents of laceration of coronary arteries and their branches leading to cardiac tamponade, and death. . . . Because of such incidents, one often waits until the very last moment and valuable time is wasted. Therefore I started to look for a new way to approach the heart, and I catheterized the right side of the heart through the venous system."³

The potentials of Forssmann's technique as a diagnostic tool were appreciated by others. In 1930, Klein reported 11 right heart catheterizations, including passage to the right ventricle and measurement of cardiac output using Fick's principle.⁴ The cardiac outputs were 4.5 and 5.6 L/min in two patients without heart disease. In 1932 Padillo and co-workers reported right heart catheterization and measurement of cardiac out-

put in two subjects.² Except for these few studies, application of cardiac catheterization to study of the circulation in normal and disease states was fragmentary until the work of Andre Cournand and Dickinson Richards, who separately and in collaboration produced a remarkable series of investigations of right heart physiology in man.⁵⁻⁷ In 1947 Dexter reported his studies on congenital heart disease.⁸ He went further than his predecessors by passing the catheter to the pulmonary artery, and in addition he mentioned some observations on "the oxygen saturation and source of pulmonary capillary blood" obtained from the pulmonary artery "wedge" position.⁹ Subsequent studies from Dexter's laboratory¹⁰ and by Werko¹¹ elaborated on this pulmonary artery "wedge" position, and pressure measured at this posi-

tion was reported to be a good estimate of pulmonary venous and left atrial pressure. During this exciting early period, catheterization was used to investigate problems in cardiovascular physiology by McMichael in England,¹² Lènegre in Paris,¹³ and Warren, Stead, Bing, Dexter, Courmand, and others in this country.¹⁴⁻²³

Further developments came rapidly. To touch briefly on some of the highlights: Retrograde left heart catheterization was first reported by Zimmerman²⁴ and Limon Lason²⁵ in 1950. The percutaneous technique developed by Seldinger in 1953²⁶ was soon applied to cardiac catheterization of both the left and right heart chambers.²⁶ Transseptal catheterization was first developed in 1959 by Ross²⁷ and Cope²⁸ and quickly became accepted as a standard technique. Selective coronary arteriography was developed by Sones in 1959 and perfected to a remarkable excellence over the ensuing years.^{29,30} This technique was modified for a percutaneous approach by Ricketts and Abrams³¹ in 1962 and Judkins³² in 1967. In 1970 a practical balloon-tipped flow-guided catheter technique was introduced by Swan and Ganz, making possible the applicability of catheterization outside the catheterization laboratory.³³

In the more recent past, investigators have focused once again on the therapeutic potential of the cardiac catheter. In 1977, Grüntzig introduced the technique of coronary angioplasty.^{34,35} In the ensuing years, the method was widely applied and with rapidly evolving technology appears to be developing a firm position rivaling coronary bypass surgery as a therapeutic modality for coronary artery disease. Intracoronary administration of thrombolytic agents in patients with acute myocardial infarction was introduced in the late 1970s, and rapidly gained acceptance as a treatment for acute myocardial infarction due to coronary thrombosis.³⁶⁻³⁸

There are many other landmarks that could be mentioned, and many individuals whose contributions should be recognized. The interested reader is referred elsewhere for details.³⁹⁻⁴⁰

INDICATIONS FOR CARDIAC CATHETERIZATION

As performed today, cardiac catheterization may be defined as a combined hemody-

namic and angiographic procedure undertaken for diagnostic or therapeutic purposes.

As with any invasive procedure, the decision to perform cardiac catheterization must be based upon a careful balance of the risk of the procedure against the anticipated benefit to the patient. Cardiac catheterization is generally recommended when there is a need to confirm the presence of a clinically suspected condition, define its anatomic and physiologic severity, and determine the presence or absence of associated conditions. This need most commonly arises when the clinical assessment suggests that the patient is approaching the stage of rapid deterioration, incapacitation, and death when viewed in the context of the natural history of his or her specific disorder. Cardiac catheterization may yield information that will be crucial in defining the need for cardiac surgery, coronary angioplasty, or other therapeutic interventions as well as timing, risks, and anticipated benefit in a given patient.

Is Cardiac Catheterization Necessary in All Patients Being Considered for Cardiac Surgery. Although few would disagree that consideration of heart surgery is an adequate reason for the performance of catheterization, there are differences of opinion about whether *all* patients being considered for heart surgery should undergo preoperative cardiac catheterization. In this regard, at least one recent study⁴¹ concluded that routine cardiac catheterization is unnecessary before valve replacement but can be reserved for specific indications in some patients. There has been sharp disagreement with this conclusion by at least two authorities,⁴²⁻⁴³ who pointed out that information concerning concomitant coronary artery obstruction, pulmonary hypertension, and other associated conditions cannot be precisely obtained without cardiac catheterization. In a study of 108 consecutive patients referred for cardiac catheterization, noninvasive evaluation led to diagnostic predictions that were completely correct in 86% of patients.⁴⁴ A "management strategy" (choice of (1) no catheterization, no operation; (2) no catheterization, operation; (3) cardiac catheterization required before decision regarding operation) was decided upon, based on the clinical and noninvasive evaluation, and this management strategy was subsequently evaluated by comparison with the findings of the actual cardiac catheterization, which followed noninvasive evaluation in every pa-

TABLE 1-1 *Correctness of Suggested Management Strategies Based on Clinical and Full Noninvasive Studies in 108 Patients*

Suggested Strategy	Number of Patients	Errors
No catheterization; no operation	19/108 (18%)	3/19 (16%)
No catheterization; operation	30/108 (28%)	0/30 (0%)
Catheterization	59/108 (54%)	0/59 (0%)

tient.⁴⁴ The results are summarized in Table 1-1.

Thus, although clinical and noninvasive evaluation are usually adequate for clinical decision making, there was a 16% error rate in devising an appropriate management strategy in one category of strategy. In this regard I would emphasize that the risks of catheterization are small compared to those of cardiac surgery in a patient with an incorrect clinical diagnosis or in a patient in whom the presence of an unsuspected additional condition greatly prolongs and complicates the planned surgical approach. *The operating room is not a good place for surprises:* cardiac catheterization can provide the surgical team with a precise and complete roadmap of the course ahead and thereby permit a carefully reasoned and maximally efficient operative procedure. Furthermore, information obtained by cardiac catheterization may be invaluable in the assessment of crucial determinants of prognosis, such as left ventricular function and the patency of the coronary arteries. For these reasons, I recommend cardiac catheterization in virtually all patients in whom heart surgery is contemplated.

There are other major therapeutic considerations besides heart surgery that may depend upon the type of information afforded by cardiac catheterization. For example, pharmacologic intervention with heparin in suspected acute pulmonary embolism, or with high doses of propranolol and/or calcium antagonists in suspected hypertrophic subaortic stenosis might well be considered decisions of sufficient magnitude to warrant confirmation of the diagnoses by angiographic and hemodynamic investigation.

A second broad indication for performing cardiac catheterization is to diagnose obscure or confusing problems in heart disease, even when a major therapeutic decision is not imminent. Currently, the most common instance of this indication in our

laboratory is presented by the patient with chest pain of uncertain etiology, in whom there is confusion regarding the presence of obstructive coronary artery disease. Both management and prognosis of this difficult problem are greatly simplified when it is known, for example, that the coronary arteries are widely patent. Another example within this category might be the symptomatic patient with a suspected diagnosis of cardiomyopathy. Although some may feel satisfied with a clinical diagnosis of this condition, the implications of such a diagnosis in terms of prognosis and therapy (such as long-term bed rest or chronic anticoagulant therapy) are so important that I feel it worthwhile to be aggressive in ruling out potentially correctable conditions with certainty (e.g., pericardial effusive-constrictive disease), even though the likelihood of their presence may appear remote on clinical grounds.

Research. On occasion, cardiac catheterization is performed primarily as a research procedure. Although research is conducted to some degree in nearly all routine diagnostic studies performed in our laboratory, this is quite different from catheterization for the sole purpose of a research investigation. Such studies should be carried out only under the direct supervision of an experienced investigator who is expert in cardiac catheterization, using a protocol that has been carefully scrutinized and approved by the Human Studies Committee at the investigator's institution, and after a thorough explanation has been made to the patient detailing the risks of the procedure and the fact that the purpose of the investigation is to gather research information.

CONTRAINDICATIONS

If it is important to carefully consider the indications for cardiac catheterization in

each patient, it is equally important to determine whether there are any contraindications. Over the past several years, our concepts of contraindications have been modified because patients with acute myocardial infarction, cardiogenic shock, intractable ventricular tachycardia, and other extreme conditions have tolerated catheterization and coronary arteriography surprisingly well. At present the only absolute contraindication to cardiac catheterization in our laboratory is the refusal of a mentally competent patient to consent to the procedure.

A long list of *relative* contraindications must be kept in mind, however, and these include all intercurrent conditions that can be corrected and whose correction would improve the safety of the procedure. These relative contraindications are listed in Table 1-2. For example, ventricular irritability can increase the risk and difficulty of left heart catheterization and can greatly interfere with interpretation of ventriculography (see Chapter 14); it should be suppressed medically prior to catheterization. Hypertension increases predisposition to ischemia and/or pulmonary edema, and should be controlled prior to and during catheterization. Other conditions that should be controlled prior to elective catheterization include intercurrent febrile illness, decompensated left heart failure, correctable anemia, digitalis toxicity, and hypokalemia. *Allergy to radiographic contrast agent* is a relative contraindication to cardiac angiography, but with proper pre-

medication the risks of a major adverse reaction can be substantially reduced, as discussed in Chapter 3.

Anticoagulant therapy is more controversial as a contraindication. Some authors have cautioned against the use of anticoagulants, particularly when percutaneous techniques are utilized;⁴⁵⁻⁴⁸ others suggest that their use may be safe or even desirable.⁴⁹⁻⁵⁰ As pointed out in Chapters 5 and 13, heparin may lower the incidence of thromboembolic complications during coronary angiography. It is important to distinguish anticoagulation with oral anticoagulants (e.g., coumadin) from that with heparin. Heparin anticoagulation can be reversed rapidly during catheterization if necessary (e.g., perforation of the heart or great vessels, uncontrolled bleeding from femoral or brachial sites). Reversal of the prolonged prothrombin time of oral anticoagulation represents a more complex problem. *I strongly oppose acute reversal of oral anticoagulation with parenteral vitamin K* because of the occasional induction of a hypercoagulable state. This in turn may result in thrombosis of prosthetic valves or thrombus formation within cardiac chambers, arteries, or veins. If reversal of oral anticoagulation is required, I recommend administration of fresh frozen plasma. For patients chronically anticoagulated with an oral agent, I routinely recommend discontinuation of the oral anticoagulant 48 hours prior to cardiac catheterization, with heparin given during these 48 hours for the patients who have a strong indication for continuous

TABLE 1-2 *Relative Contraindications to Cardiac Catheterization and Angiography*

1. Uncontrolled ventricular irritability: the risk of ventricular tachycardia/fibrillation during catheterization is increased if ventricular irritability is uncontrolled.
2. Uncorrected hypokalemia or digitalis toxicity.
3. Uncorrected hypertension: predisposes to myocardial ischemia and/or heart failure during angiography.
4. Intercurrent febrile illness.
5. Decompensated heart failure: especially acute pulmonary edema, unless catheterization can be done with patient sitting up.
6. Anticoagulated state: prothrombin time >18 seconds.
7. Severe allergy to radiographic contrast agent.
8. Severe renal insufficiency and/or anuria: unless dialysis is planned to remove fluid and radiographic contrast load.

anticoagulation (e.g., mechanical cardiac valve prosthesis). I prefer to have the prothrombin time less than 18 seconds and no heparin administration for 4 hours prior to the catheterization. If anticoagulant therapy cannot be interrupted at all, I prefer heparin for the reasons just mentioned.

FACTORS INFLUENCING CHOICE OF APPROACH

Of the various approaches to cardiac catheterization, certain ones have only historical interest (transbronchial approach, posterior transthoracic left atrial puncture, suprasternal puncture of the left atrium). In this book we will discuss in detail only (a) catheterization by direct exposure of artery and vein, and (b) catheterization by percutaneous approach (including transseptal catheterization). Left ventricular puncture will be mentioned briefly, although this has not been required in our laboratory in several years.

By either the direct or percutaneous approach (or a combination of both), the great vessels and all cardiac chambers can be entered in nearly all cases. Each method has its advantages and disadvantages, its adherents and detractors. In reality, the methods are not mutually exclusive but rather complementary, and the physician performing cardiac catheterization should be well versed in both methods.

Advantages of the Brachial Approach. The direct exposure approach usually utilizes cutdown on the brachial artery and basilic vein at the elbow, whereas the percutaneous approach of Seldinger traditionally involves entry of the femoral artery and vein at the groin.²⁶ In recent years, percutaneous right heart catheterization from the internal jugular vein has been widely applied. The direct brachial approach may have advantages in a patient with peripheral vascular disease involving the abdominal aorta, iliac, or femoral arteries, suspected femoral vein or inferior vena caval thrombosis, or coarctation of the aorta. The direct brachial approach may also have advantages in the very obese patient, in whom the percutaneous femoral technique may be technically difficult and bleeding hard to control after catheter removal. Some prefer the

brachial approach in patients who have significant hypertension, aortic regurgitation, or wide pulse pressure from other causes, or who are receiving anticoagulants. In these three circumstances, an increased hazard of bleeding has been reported with the percutaneous femoral technique. Other advantages frequently cited for the direct brachial approach include greater catheter control, greater potential selection of catheters (end-hole, side-hole), use of a single left heart catheter/Sones catheter) for left ventriculography and coronary angiography, and greater ease of catheter exchange in case of a clotted catheter.

Advantages of the Femoral Approach. In contrast, the percutaneous femoral approach has its own broad set of advantages and indications. Arteriotomy and arterial repair are not required; it can be performed repeatedly in the same patient at intervals, whereas the brachial approach can rarely be repeated more than two or three times with safety; infection and thrombophlebitis at the catheterization site are rare; and there is no need for surgical (suture) closure of the skin. It is clearly the method of choice in a patient with absent or diminished radial and brachial pulsations, or when direct brachial approach has been unsuccessful. This last indication is important, for example, in the patient with tight aortic stenosis in whom retrograde catheterization may prove impossible; in this circumstance, percutaneous transseptal catheterization of the left atrium and ventricle is helpful (see Chapter 5). In the rare instance when retrograde arterial and transseptal catheterization have not been successful in gaining entry into the left ventricle, direct transthoracic puncture of the left ventricle may be considered.

DESIGN OF THE CATHETERIZATION PROTOCOL

Every cardiac catheterization should have a protocol, that is, a carefully reasoned sequential plan designed specifically for the individual patient being studied. Although this protocol may exist only in the mind of the operator, it is our practice to prepare a written protocol and post it in the catheteri-