



CARDIOPULMONARY BYPASS

PRINCIPLES
AND PRACTICE

THIRD EDITION

GLENN P. GRAVLEE | RICHARD F. DAVIS
ALFRED H. STAMMERS | ROSS M. UNGERLEIDER



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Cardiopulmonary Bypass

Principles and Practice

Third Edition

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We dedicate this third edition to our previous coeditor for the first and second editions, the late Joe R. Utley, MD. Dr. Utley's long and accomplished career in cardiac surgery was marked by inspirational innovations in the science and clinical practice of cardiopulmonary bypass. We believe that Joe derived his greatest professional satisfaction from educational advancements, innovations such as an annual multidisciplinary meeting about cardiopulmonary bypass, and the development and publication of the first and second editions of Cardiopulmonary Bypass: Principles and Practice. We miss his leadership, creativity, and friendship. We sincerely hope that he would have agreed that the third edition has remained true to the principles and trajectory we established in the first two editions. Thank you, Joe.

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PREFACE

Before embarking upon this third edition of *Cardiopulmonary Bypass: Principles and Practice*, the editors considered the shrinking clinical volumes of coronary artery bypass graft procedures, recent developments in percutaneous valve surgery, and the trend toward performing coronary artery bypass grafting (CABG) procedures without cardiopulmonary bypass (CPB). Did the need for a current and comprehensive reference source on CPB still exist? Obviously, we decided that CPB is alive and well, and that the timing is appropriate to craft the third edition of our textbook. Although certain surgical applications for CPB may have diminished, a variety of other developments and trends serve as growth areas for CPB and other circulatory support interventions. The increasing prevalence of congestive heart failure has stimulated interest in surgical procedures to reshape the heart and in longer-term applications of ventricular assist devices. As our population ages, the prevalence of aortic and mitral valve disease increases, and surgical repair or replacement remains the gold standard for these diseased valves. And at the opposite end of the age spectrum pediatric cardiac surgical teams are pushing the frontiers of correction of congenital heart malformations. In so doing they require ever more sophisticated applications of CPB. Minimally invasive cardiac surgical techniques offer promise for shorter hospitalization and faster return to normal activities. Many of these techniques require CPB, often with major technological refinements and miniaturization. Such changes have substantially reduced the physiologic trespass incurred by CPB since the first edition of this book was published in 1993. Yet the increasing age and risk profile of our patient population offsets these gains and creates a demand for continued fast-paced advancement of the disciplines engaged in CPB.

Ross Ungerleider and Al Stammers are new editors for the third edition. Both individuals bring substantial

experience, expertise, and creativity to this edition. These editors represent the surgical and cardiovascular perfusion communities, respectively, thereby perpetuating the philosophy that this book should reflect the multidisciplinary nature of the clinical practice of CPB. Consequently, the editors and the chapter authors constitute a diverse mix of anesthesiologists, surgeons, cardiovascular perfusionists, and basic scientists.

This edition features a number of changes in content and organization. Rather than a single chapter, there is now an entire section with five chapters devoted to neonates, infants, and children. This makes sense, because the procedures, equipment, and complications for these patients often differ strikingly from those for adults. Two chapters have been added to specifically address patient safety and teamwork in CPB because both topics are so critical to improving patient outcomes. The hematology section has been reorganized and expanded, incorporating new chapters on coagulation testing and on pharmacologic prophylaxis for post-CPB bleeding. Since the second edition was published, the topic of minimally invasive extracorporeal circuitry has expanded beyond a single vendor and extracorporeal circuit, so Chapter 8 reflects these expanded options and applications.

As in the first and second editions, our mission is to provide a comprehensive source of clinical information about extracorporeal circulation as well as its underlying basic science principles. Practitioners and students of anesthesiology, surgery, and cardiovascular perfusion will most directly benefit from this book, but it should also appeal to neonatologists, cardiologists, and intensive care specialists.

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PREFACE TO THE FIRST EDITION

The rapidly expanding scope of medical knowledge threatens to overwhelm even our most diligent efforts to remain current, even within a discrete specialty arena. In a lecture reflecting on his noteworthy academic career in anesthesiology spanning over four decades, Dr. Joseph Artusio noted that there were just three English-language textbooks relevant to anesthesiology during his residency in the 1940s. He went on to say, "And now, there's a new book every week."* Amid this scenario, one might reasonably ask whether this, or any other new medical text, offers something new and worthwhile. This book was designed to provide comprehensive and scholarly discussion of cardiopulmonary bypass with a comprehensive multidisciplinary scope and a structure that differs considerably from previous texts in the field.

Current annual oxygenator utilization is estimated at 350,000 patients in the United States, and 650,000 patients worldwide, so the number of patients affected by this intervention is not insignificant. These numbers reflect continued growth in oxygenator utilization, and the complexity of disease present in patients undergoing cardiopulmonary bypass continues to escalate. Although cardiac surgical procedures account for the vast majority of oxygenators consumed, other indications for cardiopulmonary bypass are either emerging (e.g., cardiac arrest and supported angioplasty) or re-emerging

(e.g., pulmonary support). In the United States, the number of hospitals offering cardiopulmonary bypass is also rapidly expanding.

The clinical management of cardiopulmonary bypass for cardiac surgery represents a team effort involving perfusionists, surgeons, and anesthesiologists. Our goal has been to provide a textbook representing the perspectives of each of those professions while addressing both practical and reference needs for practitioners and trainees. We also hope to assist cardiologists, neonatologists, and intensive care specialists who manage patients undergoing or recovering from cardiopulmonary bypass. We hope that scholarly pathophysiologic discussions will enhance the understanding and application of patient care after cardiopulmonary bypass. Like most multi-author textbooks, some redundancy exists between individual chapters. We strove to minimize this, but elected to retain any overlap that appeared to enhance the understanding of the primary subject covered in a given chapter or represented an author's unique perspective on that particular subject. As with most medical subjects, when discussing cardiopulmonary bypass, the border between fact and opinion is often indistinct. Such is the nature of medicine as an imperfect science.

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Glenn P. Gravlee acknowledges his wife, Joyce Gravlee. This work would not have been possible without her patience and support.

Alfred Stammers thanks his wife and children, Alex and Zach, whose support served as constant reminder of life's most important attributes.

Ross Ungerleider devotes this book to each of you who pick it up with the hope of learning and growing as you commit yourself to caring for an increasingly complex group of patients who require our "best." He is grateful to his wife, Jamie, whose collaboration is evident in the chapter on teamwork and whose loving friendship has enriched his life. He also acknowledges his teammates at Doernbecher Children's Hospital in Portland (OHSU), whose consistent excellence and compassionate care model an environment of best practice.

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SECTION I

History

Historical Development of Cardiopulmonary Bypass in Minnesota

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A physician at the bedside of a child dying of an intracardiac malformation as recently as 1952 could only pray for a recovery. Now, with the heart-lung machine, correction is routine. As a result, open-heart surgery has been widely regarded as one of the most important medical advances of the 20th century. It is so widespread (2,000 such surgeries performed every 24 hours worldwide), performed so effortlessly, and carries such low risk at all ages that it may be difficult for the current generation of cardiologists and cardiac surgeons, much less the lay public, to appreciate that just 40 years ago the outer wall of the living human heart presented an impenetrable anatomic barrier to the surgeon's knife and to the truly incredible therapeutic accomplishments that are so commonplace now.

The keystone to this astonishing progress has been cardiopulmonary bypass (CPB) by extracorporeal circulation (ECC). These methods for ECC have allowed surgeons to empty the heart of blood, stop its beat as necessary, open any desired chamber, and safely carry out reparative procedures or even total replacement in an unhurried manner.

Beginning in 1951, a number of developments that made the transition from the research laboratory to clinical open-heart surgery possible and successful occurred in the Department of Surgery at the University of Minnesota (Table 1). This institution boasted of two unequaled assets. One was the world's first heart hospital devoted entirely to the medical and surgical treatment of heart diseases. This 80-bed facility for pediatric and adult patients was donated to the University of Minnesota by the Variety Club of the Northwest and opened its doors to patients on July 1, 1951. The second, and perhaps even more important, advantage was the presence of Owen H. Wangensteen, a truly visionary surgeon, as Chairman of the Department of Surgery. He was not a cardiac surgeon but had made immense contributions in the field of general surgery by his innovative work in the treatment and prevention of bowel obstruction.

Over the years, beginning in 1930, he had evolved the unique "Wangensteen system" for the training of young surgeons. He placed a heavy emphasis on in-depth knowledge of the basic sciences and on research. He believed that this combination of a thorough grounding in the basic sciences and the insights gained by research gave young surgeons the confidence to disregard or abandon previously held ideas and traditions and to go forward on the basis of their own judgment and knowledge.

Proverbial also was his ability to spot talent and capabilities in his younger colleagues, whose aptitudes were not at all obvious to others—often not even to themselves. He would then proceed to develop that student using a combination of intellectual stimulation and material assistance.

THE OPEN-HEART ERA IS BORN

Hypothermia

In this stimulating milieu, major accomplishments were soon forthcoming. The first of these occurred on September 2, 1952, when Dr. F. John Lewis, a medical school classmate and close personal friend, after a period of laboratory research on dogs successfully closed a secundum atrial septal defect (ASD) (1) in a 5-year-old girl under direct vision using inflow stasis and moderate total body hypothermia (Fig. 1).[‡] The date has considerable historic significance because that was the world's first successful surgery within the open human heart under direct vision. Dr. Lewis had been inspired by Bigelow et al.'s experimental studies (2) on general body hypothermia as a technique for open-heart repairs. Such surgeries became routine at the University of Minnesota Hospital, and news of these successes spread rapidly throughout the medical world.

[‡]This first patient had a normal postoperative heart catheterization. She is now the mother of two healthy children and remains entirely well, nearly 50 years after her surgery.

[†]Deceased, July 1999.