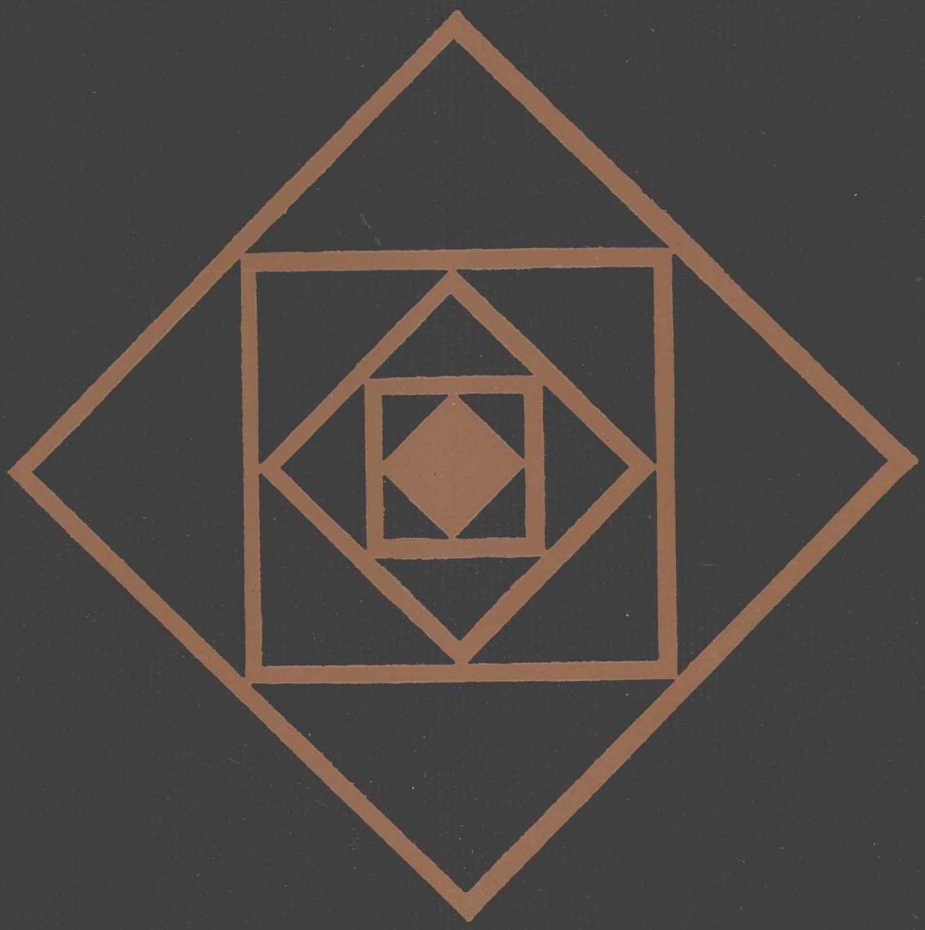
Anesthetic and Obstetric Management of High-Risk Pregnancy



Sanjay Datta

Anesthetic and Obstetric Management of High-Risk Pregnancy

Sanjay Datta, M.D., F.F.A.R.C.S.(Eng)
Associate Professor in Anaesthesia
Harvard Medical School
Director of Obstetric Anesthesia
Brigham and Women's Hospital
Boston, Massachusetts

Mosby Year Book
St. Louis Baltimore Boston Chicago London Philadelphia Sydney Toronto

Mosby
Year Book

Dedicated to Publishing Excellence

Sponsoring Editor: Susan M. Gay
Assistant Editor: Janet Livingston
Associate Managing Editor, Text and Reference:
Jan Gardner
Production Project Coordinator: Carol A. Reynolds
Proofroom Supervisor: Barbara Kelly

A Year Book Medical Publishers imprint of Mosby–Year Book, Inc.

Mosby–Year Book, Inc.
11830 Westline Industrial Drive
St. Louis, MO 63146

2 3 4 5 6 7 8 9 0 CL PC 95 94 93 92

Library of Congress Cataloging-in-Publication Data
Anesthetic and obstetric management of high-risk pregnancy/[edited by] Sanjay Datta.
p. cm.
Includes bibliographical references.
Includes index.
ISBN 0-8151-2311-6
1. Anesthesia in obstetrics. 2. Pregnancy, Complications of. 3. Labor, Complicated. 4. Pregnant women—Surgery.
[DNLM: 1. Anesthesia, Obstetrical. 2. Pregnancy Complications. WO 450 A5795]
RG732.A555 1991 91-13238
617.9′682—dc20 CIP
DNLM/DLM
for Library of Congress

To my wife, Gouri, and daughter, Nandini, whose endless encouragement, continuing understanding, and valuable help made this project possible.

CONTRIBUTORS

Ezzat Abouleish, M.D.
Professor, Department of Anesthesiology
The University of Texas Medical School
at Houston
Houston, Texas

Lindsay S. Alger, M.D.
Associate Professor
Department of Obstetrics and Gynecology
University of Maryland School of Medicine
Associate Director
Division of Maternal-Fetal Medicine
University of Maryland Medical Center
Baltimore, Maryland

Thomas J. Arcario, LCDR, MC, USNR, M.D.
Director of Obstetric Anesthesia
National Naval Medical Center
Bethesda, Maryland

Angela M. Bader, M.D.
Assistant Professor of Anaesthesia
Harvard Medical School
Staff Anesthesiologist
Brigham and Women's Hospital
Boston, Massachusetts

T.F. Baskett, M.B., F.R.C.S.C., F.R.C.S.(Ed), F.R.C.O.G.
Professor, Department of Obstetrics and
Gynecology
Dalhousie University
Chief, Department of Gynecology
Halifax Infirmary
Halifax, Nova Scotia

Gerard M. Bassell, M.B., B.S.
Professor of Anesthesiology, Obstetrics and
Gynecology
Vice Chairman
Department of Anesthesiology
Director of Obstetric Anesthesia
University of Kansas School of Medicine
at Wichita
Wichita, Kansas

Richard E. Besinger, M.D.
Assistant Professor
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
Loyola University Medical Center
Maywood, Illinois

David J. Birnbach, M.D.
Director of Obstetric Anesthesiology
Assistant Clinical Professor of Anesthesiology
Department of Anesthesiology
Columbia University College of Physicians
and Surgeons
St. Luke's/Roosevelt Hospital
New York, New York

Norman H. Blass, M.D.
Professor of Obstetrics and Gynecology
Professor of Anesthesiology
Director, Obstetrics Anesthesia
Medical College of Virginia
Virginia Commonwealth University
Richmond, Virginia

Bryann Bromley, M.D.
Instructor in Obstetrics, Gynecology, and Reproductive Biology
Harvard Medical School
Staff, Department of Obstetrics, Gynecology, and Reproductive Biology
Brigham and Women's Hospital
Boston, Massachusetts

William R. Camann, M.D.
Instructor in Anaesthesia
Harvard Medical School
Staff Anesthesiologist
Brigham and Women's Hospital
Boston, Massachusetts

Harvey Carp, Ph.D., M.D.
Assistant Professor
Department of Anesthesia
Oregon Health Sciences University
Portland, Oregon

Curtis L. Cetrulo, M.D.
Professor of Maternal Fetal Medicine
Tufts University School of Medicine
Director of Obstetrics and Gynecology
St. Margaret's Hospital for Women
Boston, Massachusetts

Linda Chan, M.D.
Clinical Assistant Professor of Obstetrics and Gynecology
Department of Obstetrics and Gynecology
Thomas Jefferson University
Philadelphia, Pennsylvania

Theodore G. Cheek, M.D.
Assistant Professor of Anesthesia, and Obstetrics and Gynecology
Director of Obstetric Anesthesia
University of Pennsylvania Medical Center
Philadelphia, Pennsylvania

Brian Clark, Ph.D., M.D.
Clinical Fellow
Department of Obstetrics and Gynecology
Oregon Health Sciences University
Portland, Oregon

Richard B. Clark, M.D.
Director of Obstetric Anesthesia
Professor of Anesthesia
University of Arkansas for Medical Sciences
Little Rock, Arkansas

Barry C. Corke, M.B., Ch.B., F.F.A.R.C.S.(Eng)
Director of Obstetric Anesthesia
Associate Professor of Anesthesia
University of North Carolina
Chapel Hill, North Carolina

Sanjay Datta, M.D., F.F.A.R.C.S.(Eng)
Associate Professor in Anaesthesia
Harvard Medical School
Director of Obstetric Anesthesia
Brigham and Women's Hospital
Boston, Massachusetts

Sidney B. Effer, M.D., F.R.C.S.C., F.A.C.O.G.
Professor of Obstetrics and Gynecology
Division of Maternal Fetal Medicine
Associate in Anesthesia
University of British Columbia
Vancouver, British Columbia, Canada

Dan Farine, M.D.
Assistant Professor of Obstetric Gynecology
Director of Maternal Fetal Medicine
University of Toronto
Mount Sinai Hospital
Toronto, Ontario, Canada

Raphael Y. Gershon, M.D.
Fellow, Obstetric Anesthesia
Department of Anesthesiology
University of Maryland Medical Center
Baltimore, Maryland

Larry C. Gilstrap III, M.D.
Professor, Obstetrics and Gynecology
Director, Maternal-Fetal Medicine Fellowship Program and Clinical Genetics
University of Texas Southwestern Medical Center
Dallas, Texas

Bernard Gonik, M.D.
Associate Professor
Department of Obstetrics, Gynecology, and Reproductive Sciences
The University of Texas Medical School at Houston
Houston, Texas

Michael F. Greene, M.D.
Assistant Professor in Obstetrics and Gynecology, and Reproductive Biology
Harvard Medical School
Chief of Maternal Fetal Medicine
Brigham and Women's Hospital
Harvard Medical School
Boston, Massachusetts

Amos Grunebaum, M.D.
Director of Maternal-Fetal Medicine
Assistant Professor of Obstetrics and Gynecology
Department of Obstetrics and Gynecology
Columbia University College of Physicians and Surgeons
St. Luke's/Roosevelt Hospital
New York, New York

Phillip R. Hamilton, M.D.
Professor and Chairman
Department of Obstetrics and Gynecology
Temple University Hospital
Philadelphia, Pennsylvania

Hunter A. Hammill, M.D.
Assistant Professor
Department of Obstetrics and Gynecology
Section of Infectious Diseases
Baylor College of Medicine
Houston, Texas

Barbara L. Hartwell, M.D.
Instructor in Anaesthesia
Harvard Medical School
Brigham and Women's Hospital
Boston, Massachusetts

Martha A. Hauch
Instructor in Anaesthesia
Harvard Medical School
Staff Anesthesiologist
Brigham and Women's Hospital
Boston, Massachusetts

Linda Heffner, M.D., Ph.D.
Assistant Professor of Obstetrics, Gynecology, and Reproductive Biology
Staff, Department of Obstetrics, Gynecology, and Reproductive Biology
Harvard Medical School
Brigham and Women's Hospital
Boston, Massachusetts

Douglas V. Horbelt, M.D., M.A.
Professor of Obstetrics and Gynecology
Vice Chairman
Department of Obstetrics and Gynecology
Director, Division of Gynecologic Oncology
University of Kansas School of Medicine at Wichita
Wichita, Kansas

Timothy Huckaby, M.D.
Assistant Professor of Anesthesiology
Director of Obstetric Anesthesiology
Ochsner Clinic
New Orleans, Louisiana

Mark D. Johnson, M.D.
Assistant Professor of Anaesthesia
Harvard Medical School
Staff Anesthesiologist
Brigham and Women's Hospital
Boston, Massachusetts

Monica M. Jones, M.D.
Assistant Professor
Department of Anesthesiology
Baylor College of Medicine
Houston, Texas

Gary P. Kaplan, M.D., Ph.D.
Assistant Professor of Neurology
State University of New York at Stony Brook
Stony Brook, New York

Nancy B. Kenepp, M.D.
Director, Obstetric Anesthesia
Associate Professor
Department of Anesthesiology
Temple University Hospital
Philadelphia, Pennsylvania

Robert A. Kinch, M.D.
Professor of Obstetrics and Gynecology
University of Texas Medical School
Galveston, Texas

Wesley Lee, M.D.
Clinical Assistant Professor of Obstetrics and Gynecology
University of Michigan
William Beaumont Hospital
Ann Arbor, Michigan

Stephen Longmire, M.D.
Assistant Professor in Anesthesiology
Assistant Professor in Obstetrics and Gynecology
Baylor College of Medicine
Houston, Texas

Andrew M. Malinow, M.D.
Chief, Section of Obstetric Anesthesia
University of Maryland Medical Center
Assistant Professor
Departments of Anesthesiology, and Obstetrics and Gynecology
University of Maryland School of Medicine
Baltimore, Maryland

Ramon Martin, M.D., Ph.D.
Instructor in Anaesthesia
Harvard Medical School
Boston, Massachusetts

Graham H. McMorland, M.B., Ch.B., D.A., F.R.C.P.C.
Clinical Professor of Anesthesia and Pharmaceutical Sciences
Associate in Obstetrics and Gynecology
University of British Columbia
Vancouver, British Columbia, Canada

Mark C. Norris, M.D.
Associate Professor of Anesthesiology
Co-Director of Obstetric Anesthesia
Department of Anesthesiology
Thomas Jefferson University
Philadelphia, Pennsylvania

Warren N. Otterson, M.D.
Professor and Chairman
Department of Obstetrics and Gynecology
Louisiana State University School of Medicine
Shreveport, Louisiana

Boris M. Petrikovsky, M.D., Ph.D.
Assistant Professor of Obstetrics and Gynecology
State University of New York at Stony Brook
Stony Brook, New York

Jim Pivarnik, Ph.D.
Associate Professor of Human Performance
Department of Health and Human Performance
The University of Houston
Houston, Texas

J. Gerald Quirk, Jr., M.D., Ph.D.
Director of Obstetrics
Professor of Obstetrics and Gynecology
University of Arkansas
Little Rock, Arkansas

Dale P. Reisner, M.D.
Assistant Professor of Obstetrics and Gynecology
Tufts University School of Medicine
Fellow in Maternal Fetal Medicine
St. Margaret's Hospital for Women
Boston, Massachusetts

Stephen Rolbin, M.D.C.M.
Assistant Professor of Anesthesia
Director of Obstetric Anesthesia
University of Toronto
Toronto, Ontario, Canada

Leonard E. Safon, M.D.
Associate Clinical Professor in Obstetrics and Gynecology and Reproductive Endocrinology
Harvard Medical School
Boston, Massachusetts

Daniel H. Saltzman, M.D.
Assistant Professor of Obstetrics, Gynecology, and Reproductive Biology
Harvard Medical School
Medical Director of Labor and Delivery
Brigham and Women's Hospital
Boston, Massachusetts

Philip Samuels, M.D.
Assistant Professor of Obstetrics and Gynecology
Director, Resident Education
University of Pennsylvania Medical Center
Philadelphia, Pennsylvania

Alan C. Santos, M.D.
Assistant Professor of Anesthesiology, Obstetrics and Gynecology
Health Sciences Center
State University of New York at Stony Brook
Stony Brook, New York

John W. Seeds, M.D.
Associate Professor of Obstetrics and Gynecology
Director of Maternal Fetal Medicine
University of North Carolina
Chapel Hill, North Carolina

Michael N. Skaredoff, M.D.
Associate Professor
Division of Obstetrical Anesthesia
Department of Anesthesiology
Department of Obstetrics and Gynecology
Loyola University Medical Center
Maywood, Illinois

Jonathan H. Skerman, B.D.Sc., M.Sc.D., D.Sc.
Professor of Clinical Anesthesiology
Professor of Obstetrics and Gynecology
Director of Obstetric Anesthesia
Louisiana State University School of Medicine
Shreveport, Louisiana

Maya S. Suresh, M.D.
Associate Professor of Anesthesiology
University of Texas Medical School
Galveston, Texas

Ronald L. Thomas, LCDR, MC, USN, M.D.
Head, Division of Maternal-Fetal Medicine
National Naval Medical Center
Bethesda, Maryland

Ruth E. Tuomala, M.D.
Assistant Professor in Obstetrics and Gynecology, and Reproductive Biology
Harvard Medical School
Director, Obstetrics and Gynecology, Infectious Diseases
Brigham and Women's Hospital
Boston, Massachusetts

Donald H. Wallace, M.D.
Associate Professor of Clinical Anesthesiology and Obstetrics and Gynecology
University of Texas Southwestern Medical Center
Director of Obstetrical Anesthesia
Parkland Memorial Hospital
Dallas, Texas

W.D.R. Writer, M.B., F.F.A.R.C.S., F.R.C.P.C.
Professor, Department of Anesthesia
Associate Professor
Department of Obstetrics and Gynecology
Dalhousie University
Chief of Anesthesia
Grace Maternity Hospital
Halifax, Nova Scotia, Canada

FOREWORD

The City of Boston has distinguished itself in the development of anesthesia in general and of obstetric pain relief in particular. The first public demonstration of successful anesthesia occurred at Massachusetts General Hospital on October 16, 1846, when William T. G. Morton administered ether by inhalation to a young man before removal of a tumor of the neck. Six months later, on April 7, 1847, Walter Channing, Professor of Midwifery and Jurisprudence at the University of Cambridge, was the first American physician to perform an obstetric procedure with the patient under anesthesia. The patient was Fanny Longfellow, the wife of the poet, Henry Wadsworth Longfellow, and both husband and wife declared this to be "a gift from God." Channing, greatly impressed with ether anesthesia for use in parturition, collected 581 cases, which he published in 1848 as the first American text on obstetric pain relief, under the title *A Treatise on Etherization in Childbirth*. Boston was also the site of the first full-time director of obstetric anesthesia in the United States. In 1942 Bert B. Hershenson assumed the position of Director of Anesthesiology at the Boston Hospital for Women, which had been founded (under the name of Lying-in Hospital) by Walter Channing.

This book, *Anesthetic and Obstetric Management of High-Risk Pregnancy*, edited by Sanjay Datta, will be another first coming out of Boston. Of the 30 chapters, 28 are authored by at least two specialists, an anesthesiologist, an obstetrician, and if indicated, a medical specialist; the two remaining chapters are written by physicians either certified or trained in both anesthesiology and obstetrics. Thus all chapters view their respective problems from two angles. Although Robert Hingson, a most respected anesthesiologist, published two volumes in conjunction with obstetricians (Lull and Hingson, 1944; Hingson and Hellman, 1958), high-risk complications were not emphasized. Thus this new text initiates a special aspect: collaboration between the specialists involved in the management of a difficult delivery.

GERTIE F. MARX, M.D.
PROFESSOR OF ANESTHESIOLOGY
ALBERT EINSTEIN COLLEGE OF MEDICINE
BRONX, NEW YORK

PREFACE

One of the most challenging yet gratifying aspects of obstetric anesthesia is its unpredictability. Obstetric anesthesiologists must continuously anticipate possible problems and tailor strategy and management accordingly. This problem becomes more apparent in parturients at high risk. Hence continuous communication and interaction between obstetrician and anesthesiologist are vital in the proper management of these complicated cases.

Even though these two specialties must work so closely together, to my knowledge no book jointly written by an anesthesiologist and an obstetrician has been published recently. I believed such a book would be a useful consultative tool for the front-line physicians and medical caretakers of high-risk pregnancies.

The majority of the chapters were contributed by members of both specialties, with the cause, pathophysiology, and obstetric treatment written by the obstetrician and anesthetic management by the obstetric anesthesiologist. One of the most important objectives was close interaction between the two specialties in finalizing the content of each chapter.

Chapter 1 describes the parameters currently used to observe fetal well-being and deals with abnormal findings that can predict intrauterine fetal problems. Chapter 4 deals with state-of-the-art obstetric and anesthetic management currently being used for intrauterine fetal manipulation in the treatment of congenital fetal problems. The other 27 chapters deal with various maternal and fetal problems, with either the mother or baby, or both, in high-risk pregnancy and delivery situations. Appropriately, the last chapter deals with the management of intrauterine fetal death.

All efforts have been made to include experts in the fields of both obstetrics and obstetric anesthesia from the United States and Canada. I thank the authors for their valuable contributions and their time and effort expended. It is also to be noted that the authors expressed their own opinions and recommendations, which do not necessarily reflect mine.

I sincerely hope that this book will be a proper reflection of the important concept of team approach, which all would agree is the vital cornerstone for maternal and fetal well-being.

Sanjay Datta, M.D., F.F.A.R.C.S.(Eng)

CONTENTS

CHAPTER 1

Prepartum and Intrapartum Fetal Monitoring

Ramon Martin, M.D., Ph.D., *Anesthesiologist*

During the 9 months of pregnancy the fetus develops in utero and is not directly accessible to evaluation. The monitoring of the mother and fetus during this period of development has evolved considerably due to biochemical and technical advances, and as a result, a better understanding of the fetus has been gained. Most pregnancies proceed and end with no complications. Monitoring techniques are used not only for diagnostic purposes, thereby serving a preventive role, but they are also necessary in treatment, if the fetus should become stressed. Stress to the fetus is defined in this chapter as either hypoxia or asphyxia. This is because the supply of oxygen to the fetus is crucial. Any diminution or cessation of oxygen results in an immediate change in acid base status, affecting all organs, particularly the heart and brain. There are compensatory responses by the fetus, but fetal reserves are limited. It is therefore important to recognize the fetal response to stress, identify the cause, and treat it.

Anesthesia, as an integral part of obstetric delivery, can impact the outcome of delivery, depending on the status of the fetus. For this reason, it is important to understand the monitoring devices used, their results, and the ultimate interpretation of the underlying fetal pathophysiology, not only during labor and delivery, but also during the preceding 9 months. This chapter will review the relevant parts of fetal respiratory and cardiac physiology to define the fetal reaction to stress (i.e., asphyxia or hypoxia). The techniques and tests used during pregnancy, labor, and delivery will then be discussed.

FETAL CARDIOVASCULAR PHYSIOLOGY

Fetal gas exchange occurs via the placenta. Because the fetal lungs are nonfunctional, there are several shunts in the fetal circulation that allow oxygenated blood to pass from the placenta to the systemic circulation. Streaming or laminar blood flow keeps oxygenated and deoxygenated blood separate in the venous system and assumes great importance in preferentially supplying oxygenated blood to organs such as the heart, brain, and adrenal glands during periods of hypoxia.

Venous Flow From the Placenta to the Fetal Heart

Approximately 40% of fetal cardiac output goes to the placenta, with a similar amount returning to the right heart via the umbilical vein (Fig 1–1). The blood in the umbilical vein has the highest oxygen saturation in the fetal circulation, so its distribu-

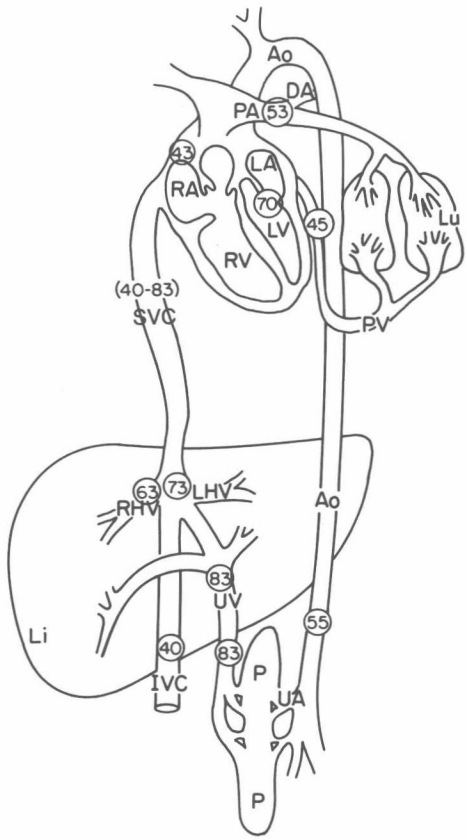


FIG 1–1.
Normal fetal circulation with major blood flow patterns and oxygen saturation values (*circled numbers* indicate percent saturation). *IVC* = inferior vena cava; *P* = placenta; *Li* = liver; *RHV* and *LHV* = right and left hepatic veins; *SVC* = superior vena cava; *RA* and *LA* = right and left atria; *RV* and *LV* = right and left ventricles; *DA* = ductus arteriosus; *PA* = pulmonary artery; *Ao* = aorta; *Lu* = lung; *DV* = ductus venosus; *PV* = pulmonary vein; *UV* = umbilical vein; UA = umbilical artery.

tion is important for the delivery of oxygen to fetal tissues. Half of the umbilical venous blood enters the ductus venosus, which connects to the inferior vena cava. The rest enters the hepatoportal venous system.[1]

Streaming, which is the separation of blood with differing oxygen saturations as it flows through a single vessel, is an important determinant of oxygen delivery to fetal tissues. This is seen when the more highly saturated umbilical venous blood passes through the ductus venosus into the inferior vena cava to meet the desaturated venous drainage from the lower trunk. In the liver, umbilical venous return is directed toward the left lobe and the portal venous return to the right lobe, so there is a marked difference in oxygen saturation (higher in the left hepatic lobe than the right).[2, 3] Although both hepatic veins enter the inferior vena cava, the left hepatic vein streams preferentially with the blood flow from the ductus venosus,[3] whereas the right hepatic vein flow follows the same route as that from the abdominal vena cava.

There is preferential flow of the umbilical venous return to the left atrium because of the crista dividens, which splits the inferior vena cava blood flow into two streams. One stream includes the oxygenated blood from the umbilical vein that is directed toward the foramen ovale and into the left atrium; the other stream consists of deoxygenated blood from the lower extremities and portal vein that enters the right atrium. This results in a higher oxygen saturation in the left atrium than the right. Blood flow through the superior vena cava is also preferentially streamed along with blood flow through the coronary sinus via the tricuspid valve. The desaturated blood from the right heart is then directed toward the placenta for reoxygenation. The left heart supplies oxygenated blood for the brain.

Cardiac Output

Because of intracardiac and extracardiac shunts, the two ventricles do not work in series, as in adults. Therefore, they do not have the same stroke volume. The right ventricle ejects approximately two thirds of fetal cardiac output (300 mL/kg/min), and the left ventricle ejects about one third (150 mL/kg/min). Of the right ventricular output, only a small fraction (8%) flows through the pulmonary arteries. Most of the output crosses the ductus arteriosus and enters the descending aorta, allowing deoxygenated

blood to return preferentially to the placenta. The left ventricular output enters the ascending aorta, and most of the output reaches the brain, upper thorax, and arms.

This distribution of cardiac output to individual organs is shown in Table 1–1. Since flow to the organs below the diaphragm is derived from both ventricles, flow is expressed as a percent of the combined ventricles.

Myocardial Function

The fetal myocardium, relative to the adult myocardium, is immature in structure, function, and sympathetic innervation. Although the length of the fetal sarcomere is the same as that in the adult,[7] the diameter of the fetal sarcomere is smaller and the proportion of noncontractile mass to the number of myofibrils is less, 30% in the fetus vs. 60% in adults.[8] Active tension generated by fetal myocardium is less than that in the adult heart at all lengths of a muscle along a length-tension curve. Passive or resting tension is higher in fetal myocardium than in the adult, suggesting lower compliance for the fetus. A study with volume loading by infusion of blood or saline solution in fetal lambs showed that the right ventricle is unable to increase stroke work or output as much as the adult.[9] Cardiac output varies directly with heart rate, so an increase in rate from 180 to 250 beats/min will increase cardiac output 15% to 20%. Conversely, a decrease in heart rate below basal levels causes a decrease in ventricular output. Histochemical staining of the sympathetic nervous system demonstrates delayed development. Isolated fetal cardiac tissue has a lower response threshold to the inotropic effects of norepinephrine compared to the adult. This is presumed to be secondary to the incomplete development of the sympathetic nervous system.[8] As a result, the fetal heart appears to operate at or near peak performance normally.

TABLE 1–1.
Distribution of Cardiac Output in Fetal Lambs

Organ	Blood Flow (mL/kg/min)	Cardiac Output (%)
Heart	180	2
Brain	125	2
Upper body	25	16
Lungs	100	8
GI tract	70	5
Kidneys	150	2.5
Adrenals	200	0.1
Spleen	200	1.2
Liver	20	1.5
Lower body	25	20
Placenta	20	37

Control of the Cardiovascular System

The cardiovascular system is controlled by a complex interrelationship between autoregulation, reflex effects, hormonal substrates, and the autonomic nervous system. Whereas many organs in adults are able to maintain fairly constant blood flow over a wide range of perfusion pressures, the placental circulation does not exhibit autoregulation.[10] As a result, blood flow changes directly with changes in arterial perfusion pressure. Papile et al. demonstrated in fetal lambs that the cerebral circulation does autoregulate itself.[11] The baroreflex has also been shown to exist in fetal animals. In adults it functions to stabilize heart rate and blood pressure, but in the fetus it is relatively insensitive. Marked changes in pressure are required to produce minor responses, so that the function of the baroreflex is probably minimal in utero.[12]

The chemoreceptor reflex is governed by receptors in either the carotid body or in the central nervous system (CNS) and causes hypertension and mild tachycardia with increased respiratory activity. Chemoreceptors in the aorta cause bradycardia with a slight increase in blood pressure. The former are less sensitive than the latter so that bradycardia and hypertension are seen with hypoxia because of the overriding response of the aortic chemoreceptors.

The autonomic nervous system is fully developed in the fetus, as demonstrated by the presence of receptors and an acetylcholinesterase and its responses to cholinergic or adrenergic agonists. The renin-angiotensin system is also important in regulating the normal fetal circulation and the response to hemorrhage. Angiotensin II exerts a tonic vasoconstriction on the peripheral vasculature to maintain systemic arterial blood pressure and umbilical blood flow.[13] Vasopressin, although detectable in the fetus, probably has little regulatory function. Stress, i.e., hypoxia, elicits an increase in vasopressin secretion and results in hypertension and bradycardia.[14] In the presence of decreased cardiac output, the renin-angiotensin system maintains the flow to the brain, heart, and placenta, while flow to the splanchnic bed decreases.[15] Circulating prostaglandins are present in high concentrations in the fetus,[16, 17] and are produced by both the placenta and fetal vasculature. Prostaglandins have diverse effects on the cardiovascular system. Infusion of PGE_1, PGE_2, PGF_2 and thromboxane constricts the umbilical-placental circulation,[18, 19] whereas prostacyclin has the opposite effect. Prostaglandin E_1, PGE_2, PGI_2, and PGD_2 cause pulmonary vasodilation in the fetus and PGF_2 produces vasoconstriction.[20, 21] Prostaglandins also relax smooth muscle in the ductus arteriosus, so that it remains patent in utero.[22, 23]

PLACENTAL RESPIRATORY GAS EXCHANGE AND FETAL OXYGENATION

The passage of oxygen from the atmosphere to the fetus can be described in a sequence of six steps. These steps alternate bulk transport of gases with diffusion across membranes. The first three steps are primarily maternal and the last three steps are fetal (Fig 1–2).

Transport of oxygen starts from the atmosphere to the maternal alveoli through the large airways by the respiratory muscles, in exchange for carbon dioxide. The pressure of oxygen in the alveoli is regulated by several mechanisms that respond to changes in the levels of the partial pressures of oxygen (Po_2) and carbon dioxide (Pco_2), and the pH of maternal blood. Arterial Pco_2 in the parturient is regulated at a lower level than in the nonpregnant woman, secondary to the effects of progesterone.[24]

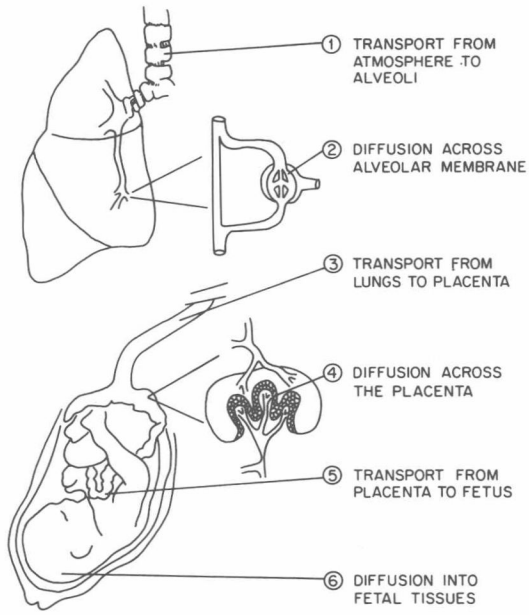


FIG 1–2.
Six steps in the transport of oxygen from the atmosphere to the fetal tissues.

With the second step, oxygen diffuses rapidly across the alveoli to maternal erythrocytes. The Po_2 of maternal arterial blood is slightly less than that in the alveoli because of shunting and inequality of ventilation and perfusion throughout the lung fields. In the pregnant woman, the gradient of oxygen in the arterioles and alveoli is dependent on position and widens when going from the upright to the supine position.

Maternal blood transports oxygen to the placenta in two forms, free and bound to hemoglobin. These two forms are in a reversible equilibrium.

In the diffusion of oxygen across the

placenta, the oxygen uptake by the gravid uterus is greater than that by the fetus. This is because the placenta and the uterus extract oxygen and consume a relatively large fraction compared to the fetus. In chronic sheep preparations, this has been calculated with the Fick principle: Uterine oxygen consumption is measured by the difference in oxygen content between the maternal arterial blood (A) and uterine venous blood (V). Multiplying the difference by uterine blood flow (F) yields uterine oxygen uptake:

$$(A - V)F = O_2 \text{ uptake by the gravid uterus}$$

In a sheep study the umbilical vein was observed to carry the highest concentrations of oxygenated blood delivered to the fetus, but this is low when compared with maternal Po_2. Attempts have been made to explain the low fetal Po_2 with either a concurrent or crosscurrent model of oxygen placental exhange, but the placenta is probably more complex. Nonetheless, the umbilical venous Po_2 depends on and is not higher than the venous Po_2 of the uterine circulation.[25] In addition, three other factors might contribute to the inefficiency of the exchange process:

1. Shunting—the diversion of blood away from the exchange surface to perfuse the myometrium and endometrium.
2. Uneven perfusion—differences in the ratio of maternal-fetal blood flow can vary in portions of the placenta.
3. Oxygen diffusing capacity is defined as the product of the quantity of oxygen transferred from maternal to fetal circulation divided by the mean Po_2 difference between maternal and fetal erythrocytes. It is the result of the permeability of the placental membrane to oxygen transport and of the reaction rate of oxygen with hemoglobin.[26]

Uterine venous Po_2, a primary factor that determines umbilical venous Po_2, is in turn influenced by a number of other factors (see box). Chief among these are the oxygen saturation and the oxyhemoglobin dissociation curve of venous blood. The oxyhemoglobin dissociation curve is shifted by pH so that Po_2 is inversely related to pH (Bohr effect). As a result, maternal alkalosis will shift the curve to the left, decreasing oxygen delivery to the fetus. Other factors that can shift the curve are temperature, hemoglobinopathies and the 2,3-diphosphoglycerate (2,3-DPG) content of erythrocytes. Oxygen saturation of uterine venous blood (Sv) is a function of four variables: maternal arterial oxygen saturation (Sa), oxygen capacity of maternal blood (O_2Cap), uterine blood flow (F), and the oxygen consumption rate (Vo_2) of the gravid uterus (including placental and fetal oxygen consumption). This can be formulated as

Factors That Determine Uterine Venous Po_2

- Oxyhemoglobin dissociation of maternal blood
  - Hemoglobin structure
  - Temperature
  - Erythrocyte pH (2, 3-DPG)
- Oxygen saturation in uterine venous blood
  - Arterial O_2 saturation
  - Uteroplacental blood flow
  - O_2 capacity
  - Placental and fetal O_2 consumption

$$Sv = Sa - Vo_2/F(O_2Cap)$$

which is an application of the Fick principle. Anemic, circulatory, or hypoxic hypoxia will decrease uterine venous saturation, leading to a decrease in fetal oxygenation.

Although umbilical vein Po_2 is less than that in the maternal circulation, there are compensatory mechanisms to ensure adequate fetal oxygenation. Fetal erythrocyte hemoglobin has a high affinity for oxygen. The rate of perfusion of fetal organs, compared with that in adults, is high in relation to their oxygen requirements. Physiologically, the low level of Po_2 in fetal arterial blood is a part of the mechanism that keeps