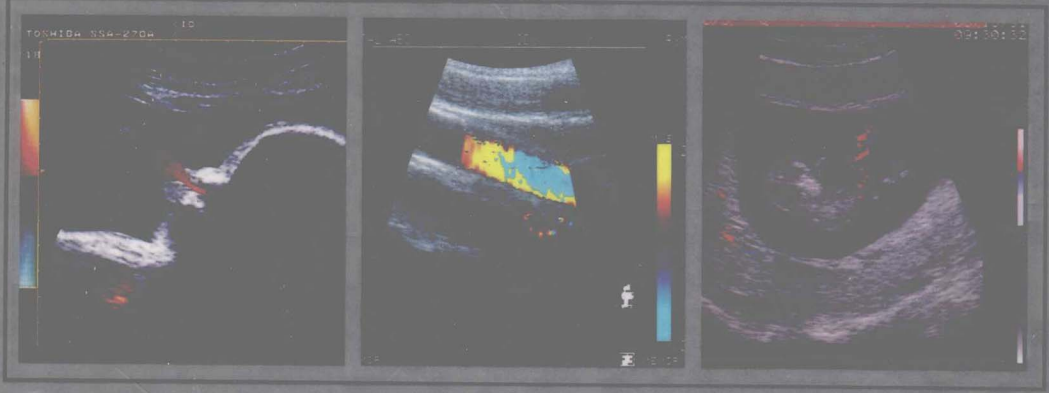
COLOR DOPPLER IMAGING



in Obstetrics and Gynecology

RICHARD JAFFE / STEVEN L. WARSOF

COLOR DOPPLER IMAGING IN OBSTETRICS AND GYNECOLOGY

Editors

RICHARD JAFFE, M.D.

Assistant Professor
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
University of Illinois at Chicago
Chicago, Illinois

STEVEN L. WARSOF, M.D.

Associate Professor, Director
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
University of Illinois at Chicago
Chicago, Illinois

McGRAW-HILL, INC.

Health Professions Division

New York St. Louis San Francisco Auckland Bogotá Caracas Lisbon
London Madrid Mexico Milan Montreal New Delhi Paris San Juan
Singapore Sydney Tokyo Toronto

COLOR DOPPLER IMAGING
IN OBSTETRICS AND GYNECOLOGY

1 2 3 4 5 6 7 8 9 0 KGPKGP 9 8 7 6 5 4 3 2

ISBN 0–07–105420–0

This book was set in Times Roman by Arcata Graphics/Kingsport.
The editors were Edward M. Bolger and Muza Navrozov;
the production supervisor was Richard Ruzycka;
the cover was designed by José Fonfrias;
the index was prepared by Philip James.
Arcata Graphics/Kingsport was printer and binder

Library of Congress Cataloging-in-Publication Data

Color Doppler imaging in obstetrics and gynecology/editors,
Richard Jaffe, Steven L. Warsof.
p. cm.
Includes bibliographical references and index.
ISBN 0–07–105420–0
1. Doppler ultrasonography. 2. Ultrasonics in obstetrics.
3. Fetus—Ultrasonic imaging. 4. Generative organs, Female—
Ultrasonic imaging. I. Jaffe, Richard. II. Warsof, Steven L.
[DNLM: 1. Echocardiography, Doppler. 2. Genital Diseases, Female—
ultrasonography. 3. Pregnancy Complications—ultrasonography.
4. Ultrasonography, Prenatal. WQ 202 C719]
RG527.5.U48C65
618′.047543—dc20
DNLM/DLC
for Library of Congress

92–6257
CIP

COLOR DOPPLER IMAGING IN OBSTETRICS AND GYNECOLOGY

NOTICE

Medicine is an ever-changing science. As new research and clinical experience broaden our knowledge, changes in treatment and drug therapy are required. The authors and the publisher of this work have checked with sources believed to be reliable in their efforts to provide information that is complete and generally in accord with the standards accepted at the time of publication. However, in view of the possibility of human error or changes in medical sciences, neither the editors nor the publisher nor any other party who has been involved in the preparation or publication of this work warrants that the information contained herein is in every respect accurate or complete, and they are not responsible for any errors or omissions or for the results obtained from use of such information. Readers are encouraged to confirm the information contained herein with other sources. For example and in particular, readers are advised to check the product information sheet included in the package of each drug they plan to administer to be certain that the information contained in this book is accurate and that changes have not been made in the recommended dose or in the contraindications for administration. This recommendation is of particular importance in connection with new or infrequently used drugs.

To our wives, Jaffa and Valerie,
and our children, Adi, Shirley,
Beth, Alison, and Elliot,
for their love and understanding.

Contributors*

Jacques Abramowicz, M.D. [12]
Assistant Professor of Obstetrics and Gynecology
Director Perinatal Ultrasound
Department of Obstetrics and Gynecology
Strong Memorial Hospital
The University of Rochester School of Medicine and Dentistry
Rochester, New York

Domenico Arduini, M.D. [11]
Deputy Director, Perinatal Unit
Department of Obstetrics and Gynecology
Catholic University of S. Cuore
Rome, Italy

Joseph G. Bell, M.D. [13]
Fellow
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
Pennsylvania Hospital
Philadelphia, Pennsylvania

Carolyn B. Coulam, M.D. [16]
Director of Reproductive Immunology
Genetics and IVF Institute
Fairfax, Virginia

Greggory R. DeVore, M.D. [8]
Fetal Diagnostic Center
Salt Lake City, Utah

Tjeerd W. A. Huisman, M.D. [9]
Division of Prenatal Diagnosis
Department of Obstetrics and Gynecology
Academic Hospital Dijkzigt
Erasmus University Rotterdam
Rotterdam, The Netherlands

Richard Jaffe, M.D. [1, 2, 4, 5, 12]
Assistant Professor
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
University of Illinois at Chicago
Chicago, Illinois

Sanja Kupesic-Urek, M.D. [14]
Ultrasonic Institute
University of Zagreb
Zagreb, Yugoslavia

Asim Kurjak, M.D. [6, 14, 15]
Professor
Ultrasonic Institute
University of Zagreb
Zagreb, Yugoslavia

* The numbers in brackets following the contributor name refer to chapter(s) authored or co-authored by the contributor.

Abraham Ludomirski, M.D. [13]
Director of Research
Department of Obstetrics and Gynecology
Pennsylvania Hospital
Philadelphia, Pennsylvania

William J. Meyer, M.D. [1]
Assistant Professor
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
University of Illinois at Chicago
Chicago, Illinois

Albert J. Peters, D.O. [16]
Fellow in Reproductive Immunology
Methodist Center for Reproduction
and Transplantation Immunology
Indianapolis, Indiana

Roger A. Pierson, M.D. [3]
Associate Professor
Reproductive Biology Research Unit
Department of Obstetrics and Gynecology
Royal University Hospital
Saskatoon, Saskatchewan
Canada

Kathryn L. Reed, M.D. [10]
Associate Professor
Head, Obstetrical Ultrasound
Department of Obstetrics and Gynecology
Arizona Health Sciences Center
Tuscon, Arizona

Giuseppe Rizzo, M.D. [11]
Perinatal Unit
Department of Obstetrics and Gynecology
Catholic University of S. Cuore
Rome, Italy

Joaquin Santolaya-Forgas, M.D., Ph.D. [7]
Assistant Professor
Division of Maternal-Fetal Medicine
Department of Obstetrics and Gynecology
University of Illinois at Chicago
Chicago, Illinois

J. Jaroslav Stern, M.D. [16]
Fellow in Reproductive Immunology
Methodist Center for Reproduction
and Transplantation Immunology
Indianapolis, Indiana

Patricia A. Stewart, Ph.D. [9]
Division of Prenatal Diagnosis
Department of Obstetrics and Gynecology
Academic Hospital Dijkzigt
Erasmus University Rotterdam
Rotterdam, The Netherlands

Juriy W. Wladimiroff, M.D., Ph.D. [9]
Professor of Obstetrics and Gynecology
Head, Division of Prenatal Diagnosis
Department of Obstetrics and Gynecology
Academic Hospital Dijkzigt
Erasmus University Rotterdam
Rotterdam, The Netherlands

Ivica Zalud, M.D. [6, 15]
Ultrasonic Institute
University of Zagreb
Zagreb, Yugoslavia

Preface

The purpose of this book is to expose the reader to the many potential areas in which color Doppler imaging can expand the clinical and research arenas for the obstetrician and gynecologist.

This book is a culmination of many years of combined experience by the authors in the use of diagnostic ultrasound. Most of the authors were introduced to ultrasound in its infancy as an A-mode curiosity of limited practical use. The contact B-mode scanner introduced in the late 1960s and gray scaling of the early 1970s raised the potential of fetal biometry. With the advent of real time imaging in the mid-1970s, the ease of imaging was greatly improved and, when combined with Doppler waveform analysis of the 1980s, biophysical assessment of the fetus became a reality. Vaginal scanning enhanced the role of the ultrasound in gynecology, gynecologic oncology, and reproductive endocrinology. Each advance in technology was heralded by a brief text designed to capture the imagination of the reader and to spur on the clinical and research community for further investigations.

We hope that after studying this text the reader will be similarly excited by the potential of color Doppler imaging. We also hope that each chapter will be the inspiration for the reader to become involved personally in new and different applications of this powerful technology.

Many years ago the late Professor Ian Donald stated that "the day may come that every gravida would have an ultrasound examination." Could he have envisioned that this examination would be in the multiple colors of the rainbow?

Ultimately, we hope that as a result of our effort the pursuit of knowledge has been advanced slightly, that the fetal-uterine environment will be better understood, and that this will lead to an improvement in maternal and child health.

Finally, we would like to thank all the authors for their timely contributions and adherence to production deadline.

Contents

CHAPTER
ONE

BASIC PRINCIPLES OF DOPPLER ULTRASONOGRAPHY

WILLIAM J. MEYER
RICHARD JAFFE

Real-time ultrasonic assessment of the fetus has become an essential component of obstetrical and perinatal practice. Ultrasound has provided a noninvasive method of monitoring and evaluation of the advancing gestation. Ultrasound is a simple, reliable method for pregnancy dating, evaluation of fetal anomalies, and assurance of fetal well-being. The advent of Doppler ultrasound has further enhanced our ability to diagnose specific fetal abnormalities such as structural and functional cardiac anomalies. Doppler velocimetry utilizes advanced technology to assess the hemodynamic status of the uterine-placental-fetal unit. Doppler ultrasound allows a unique opportunity to study the fetal and uterine circulations in normal and abnormal pregnancies, as well as enhancing our understanding of intrauterine physiology. This chapter briefly reviews the basic principles of Doppler ultrasound use in clinical medicine.

PHYSICS OF ULTRASOUND

Transmission of sound waves requires alternate compression and rarefaction of particles in a medium to create a wave.[1] Wavelength is determined by measurement of one cycle of compression and rarefaction. The frequency of this sound is the number of cycles of compression or rarefaction which pass a given point in 1 s. One cycle per second is called *one hertz* (Hz). Ultrasound is defined as a frequency greater than 20 kHz (20,000 Hz). Sound at this frequency is inaudible to the human ear. In diagnostic applications, ultrasound frequencies

range between 2 and 10 MHz.[2] The transmitted sound wave has a beam width which varies with the distance from the transducer. This determines the lateral resolution of the ultrasound image. The higher the frequency employed, the better the spatial (axial) resolution[1] but the lower the depth of penetration.

Ultrasound transducers produce high-frequency sound by short bursts of electrical stimulation of piezoelectric crystals located in the transducer. Electric voltages can produce an alteration in the crystal lattice structure of these crystals causing the crystals to vibrate and produce sound waves. This is known as the *piezoelectric phenomenon*[3] and was discovered by the Curies in 1888. The applied electrical stimulus determines the frequency and intensity of the sound wave. The same crystal receives sound, which also causes distortion of the crystal lattice, and produces electrical energy, which can be amplified and recorded. Most diagnostic transducers, which consist of many single piezoelectric elements, spend most of the time in a receiving mode with a transmit-to-receive ratio of approximately 1 : 1000. Sequential stimulation of the piezoelectric elements produces real-time images by conversion of reflected sound waves to ultrasonic images. In humans, tissue density is variable and therefore transmission speed of the ultrasound beam is variable in the various tissues. The average velocity of sound in soft tissue is approximately 1540 m/s.[4]

When an ultrasound beam travels through medium of variable density and strikes a very dense object, such as bone, most of the incident wave energy is reflected back and the transmitted wave is attenuated. This produces a bright reflected echo. Only incident waves reflected back toward the transducer produce images. The speed with which an echo returns and the intensity of returning echoes are proportional to the depth and reflectivity of objects struck by the incident wave. This is the basis of gray-scale ultrasound imaging.

THE DOPPLER EFFECT

When sound is produced by a stationary source, a wave is propagated with a given wavelength and frequency, as described above. When the source emitting sound moves relative to the receiver, the perceived frequency changes as the distance between the emitter and receiver changes. As the two objects move toward each other, the observed frequency increases, and if they move away from each other, the observed frequency decreases. The change in observed frequency is called the *Doppler shift*, which was first described by the Austrian physicist Johann Christian Doppler in 1842.[5] Doppler realized that the color emitted by a moving star changes relative to its traveling toward or away from earth. The Dutch scientist Buys-Ballot applied Doppler's finding to sound 1 year later,[6] showing that the frequency of a sound wave increases when the source of the sound approaches the receiver and decreases when the source of the sound moves away from the receiver.

This principle is applicable to any form of energy that propagates waves such as sound, light, or radio waves.

The Doppler shift occurs irrespective of whether the source, the object, or both are moving. In terms of diagnostic Doppler ultrasound, the echoes reflected by a moving echogenic object will have Doppler-shifted frequencies that depend on the velocity of the moving object and the angle between the insonating beam and the direction of motion.

The relationship between velocity of blood flow and Doppler shift is expressed by the following equation:

$$F_t - F_r = F_d = \frac{2F_t \times \cos \Theta \times v}{c}$$

where F_d = Doppler shift, F_t = transducer transmission frequency, F_r = received frequency, Θ = incident angle (between ultrasonic beam and long axis of vessel), c = velocity of sound in tissue, and v = velocity of blood flow (Fig. 1-1).

The angle between the ultrasound beam and direction of motion of the red

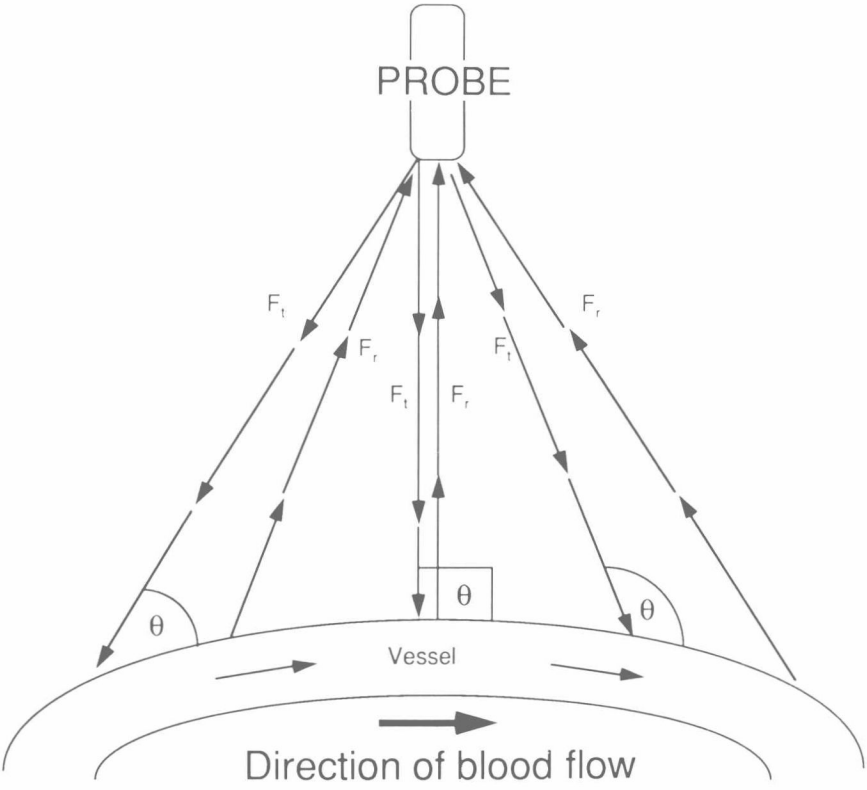


Figure 1-1 Schematic demonstration of the Doppler effect. The difference between the transmitted (F_t) and the received (F_r) frequencies is the Doppler shift (F_d), and it is dependent on the velocity of sound in the tissue (c), the transmitted frequency, the velocity of the blood (v), and the angle of insonation (θ).

blood cells is an important factor in the equation, as the Doppler shift is a consequence of motion along this line and the component of velocity is given by $v \times \cos \Theta$. Figure 1-1 shows that if the motion is perpendicular to the beam, the angle will be 90°, and as $\cos \Theta = 0$, there will be no $v \times \cos \Theta$ component and no Doppler shift. This phenomenon of zero Doppler shift is of considerable importance when evaluating color Doppler images and is discussed further in Chap. 2.

As mentioned above, the Doppler shift produced by a moving object is relative to the velocity of the object moving and the angle of the ultrasonic beam if the transmission frequency and velocity of sound in the tissue are known. When using Doppler ultrasonography to assess blood flow in an artery, the incident ultrasound beam is reflected not by one but by millions of red blood cells. When the ultrasound beam is reflected by moving red blood cells, it undergoes a reflective phenomenon called *backscattering*.[7–9] Backscattering occurs because the size of the reflective surface of the red cell is smaller than the wavelength of the ultrasonic beam. The produced echoes are scattered and reflected in all directions. The frequency shift determined by the transducer is a collection of all the Doppler shifted echoes produced by the red cells and is proportional to the velocity of the moving column of cells in the vessel. The power of the Doppler frequency shift is affected by both the RBC's concentration (hematocrit) and the turbulence of flow within the vessel.[10]

OPERATIONAL PARAMETERS

Volume Estimation

From the above equation the Doppler shift can be precisely calculated only if the angle of incidence and the velocity of blood flow in a given artery are known. Blood flow volume is measured as the product of the mean blood flow velocity and the vessel cross-sectional area (flow = velocity × cross-sectional area). Several methods have been used to estimate volumetric flow, but they all have significant limitations.[11,12] They are as follows:

1. *The uniform insonation technique.* With this technique the ultrasound beam is considered uniform, red blood cells are assumed to reflect sound equally, flow direction is assumed constant, and the sample volume is large enough to include the whole vessel. The mean velocity calculated is then multiplied by the vessel area to give volume of blood flow. Sources of error with this technique are the changes which occur in vascular shapes and diameters during the cardiac cycle, the inability to accurately measure the vessel diameter,[7,13,14] and the turbulence along vessel walls. In smaller vessels it is practically impossible to correctly measure both diameter and angle of insonation, and the error in quantitating the volume of flow can be as high as 25 to 50 percent.[15] Another source of error when employing a large sample volume is the erroneous addition of signals from outside the vessel that will affect the calculations.

2. *The velocity profile technique*. With this technique a multigated pulsed Doppler system that can assess the entire vessel at one time is used, and the individual velocity components throughout the cardiac cycle are measured and integrated. This technique also suffers from severe limitations and is not employed in clinical medicine.[2]
3. *The assumed velocity profile method*. With this method measurements are made at one point in a vessel, and the mean flow velocity assumed equal to the maximal velocity near the center of flow. This flat velocity profile is present only in large vessels such as the aorta, whereas in the smaller fetal vessels the flow profile is parabolic. Several experimental measurements have shown that this assumption is erroneous because velocity profiles were found to change over the cardiac cycle and to differ depending on location within the vessel.[2]

Because of these limitations, methods independent of incident angle and vessel diameter have been developed to estimate blood flow and analyze waveforms. These techniques all involve the calculation of different ratios derived from the shape of the spectrum maximum envelope and are discussed later in this chapter.

Sampling Volume

Sampling volume refers to that region of the Doppler system that can receive Doppler-shifted echoes and can be determined by the operator. Echoes produced within a sample volume are used to calculate the Doppler shift within that sample. In the case of blood-flow estimation, the red cells in the vessel are randomly and independently distributed within the vessel. Red cells within the sample volume generate independent echoes, which are added together to produce the final signal detected and displayed by the monitor. The sample volume is adjusted to approximate the diameter of the blood vessel being studied.[8] When the sample volume equals the vessel diameter, all parts of the vessel cross section contribute equally to the final Doppler signal, and this represents an accurate estimation of blood velocity in the given vessel. It can also be assumed that the maximum Doppler shift is proportional to the maximum velocity and that the mean Doppler shift is proportional to the mean velocity of blood flow.

In estimating flow, the diameter of the vessel may approach the lower limit of spatial resolution of the machine, and therefore vessel diameter cannot be accurately estimated. For this reason the sample volume must be sufficiently large to insolate the entire lumen of the vessel being studied.

Signal Processing

Processing the Doppler echoes involves a complex series of steps. In simple terms, the final Doppler-shifted signal which is displayed on the monitor is a summation of the scattered Doppler shifts produced by the moving column of