Doppler Ultrasound in Cardiology

Physical Principles and Clinical Applications

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Second Edition

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Second Edition

Lea & Febiger 1985 Philadelphia

Lea & Febiger
600 Washington Square
Philadelphia, PA 19106-4198
U.S.A.
(215) 922-1330

First Edition, 1982

Library of Congress Cataloging in Publication Data

Hatle, Liv.
Doppler ultrasound in cardiology.

Includes bibliographical references and index.
1. Ultrasonic cardiography. 2. Doppler effect.
I. Angelsen, Bjorn. II. Title. [DNLM: 1. Heart Diseases—diagnosis.
2. Echocardiography. WG 141.5.E2 H361d]
RC683.5.U5H37 1984 616.1'207543 84-9750
ISBN 0-8121-0936-8

PRINTED IN THE UNITED STATES OF AMERICA

Print No. 3 2 1

Preface

Recent years have seen much progress in the application of ultrasonic techniques for noninvasive diagnosis of the cardiovascular system. The greatest interest has been in ultrasonic imaging, using the amplitude of backscattered ultrasound. The Doppler shift of the backscattered sound has been used to measure the velocity of the blood. This technique has many interesting applications in the diagnosis and assessment of valve functioning and shunts, as well as in monitoring cardiac output. The usefulness of the technique was, however, overshadowed by the almost explosive evolution in real-time two-dimensional imaging of the heart. The development of combined real-time two-dimensional imaging and Doppler measurement has changed this situation. At present, about 50% of the cardiac diagnosis in our laboratory is obtained from Doppler measurements, and the other 50% is from two-dimensional imaging.

Doppler measurements are often better with a separate Doppler instrument than in combination with two-dimensional imaging because a smaller, more sensitive transducer can be used. The transducer directions that produce accurate images often do not produce the best Doppler recordings. Therefore, if one strains to obtain accurate images, the Doppler recording often suffers. The combination of real-time two-dimensional imaging and Doppler, however, is often helpful during a rapid measurement in an unambiguous location, especially in complex heart diseases such as some congenital heart lesions. The ideal instrument is therefore one that can be used as an independent Doppler instrument as well as in combination with real-time combined two-dimensional imaging.

This book, a revised second edition, is intended as an introductory text to the use of ultrasonic Doppler techniques for cardiac diagnosis. New clinical data have been added, following the development of combined real-time two-dimensional imaging and Doppler measurements. The discussion of the physical aspects of the technique has also been revised and includes new technical developments. This edition is aimed more toward clinical applications of the technique, and therefore the more advanced technical material of the first edition has been omitted. Chapters 2 and 3 present the physics of blood flow and the principles of ultrasonic Doppler techniques. Chapters 4, 5, and 6 discuss clinical applications in cardiac diagnosis. In Chapter 7, measurement of aortic flow velocity to obtain cardiac output is discussed.

Because parts of Chapters 2 and 3 are technical, it is not necessary to grasp these chapters in full detail before reading the clinical portions of the book. An introductory reading can therefore be suggested, as follows:

Chapter 1
Chapter 2, Section 2.1
Chapter 3, Sections 3.3 through 3.8
Chapters 4, 5, 6, and 7.

The rest of Chapters 2 and 3 can be read as needed.

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Acknowledgments

The material presented in this book results from a combined technical and clinical program at the University of Trondheim, Norway, for the development of ultrasonic Doppler techniques for cardiovascular diagnosis. The work has been funded by grants from the University of Trondheim, The Royal Norwegian Council for Scientific and Industrial Research, The Norwegian Council on Cardiovascular Diseases, Forenede Liv Life Insurances, Forretningsbankens Fund for Bioengineering Research, Autronica A/S. Trondheim, and Vingmed A/S, Oslo.

Several persons have participated in the work. We especially wish to acknowledge K. Kristoffersen, M.Sc., who has written part of Chapter 6 and contributed to the essential parts of the instrumentation and measurements presented in this chapter. We also wish to thank him for his cooperation during the work as well as his suggestions and comments on the technical parts of the book. We want to offer a special thanks to R. Aaslid, Dr. Philos., and A.O. Brubakk, Dr. Med., for stimulating discussions and cooperation throughout the research. We also thank Professor J.G. Balchen, head of Division of Engineering Cybernetics, The Norwegian Institute of Technology, and Professor R. Rokseth, head of Section of Cardiology, University of Trondheim, for continuous encouragement and support throughout the work.

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1 Introduction

1.1 THE DOPPLER EFFECT

If a person is moving *toward* a sound source, he will hear a tone with *higher* frequency than when he is at rest. If he is moving *away* from the source, he will hear a tone with *lower* frequency. The same phenomenon is observed when the source is moving and the observer is at rest (Fig. 1-1).

Christian Johann Doppler (1803–1853), an Austrian physicist, was the first to describe this effect. The change in frequency is called the **Doppler shift** in frequency, or simply the **Doppler frequency**.

The effect is found with all types of waves when the source and the receiver are moving relative to each other. In his paper of 1842, Doppler described how the color of the light from a star, in the same way as the pitch of a sound, is changed by the relative motion between source and observer. The same effect is used with radar waves to measure the speed of cars. When steering a boat against the waves, one will observe a higher frequency of the waves than when steering away from the waves. In everyday life, one can observe the Doppler effect from a car siren or a train whistle. When an ambulance is approaching, for example, the pitch of the siren appears to be higher than after it has passed. If the change in pitch is a whole tone step, the velocity of the car is approximately 70 km/h (45 mph).

1.2 CLINICAL USE OF ULTRASONIC DOPPLER TECHNIQUES

Ultrasound, like ordinary sound, is acoustic waves, but with a frequency above the audible range (20 to 20,000 Hz). For diagnostic purposes, frequencies in the range of 1 to 10 MHz* are used. At such high frequencies, the sound moves along straight lines like a beam of light and can be directed into the body from a handheld transducer.

The major application of diagnostic ultrasound has been for *imaging* of tissue structures. In these techniques, the *amplitude* of backscattered sound from tissue interfaces is used to generate an image, as in radar and underwater

*MHz = one million cycles per second

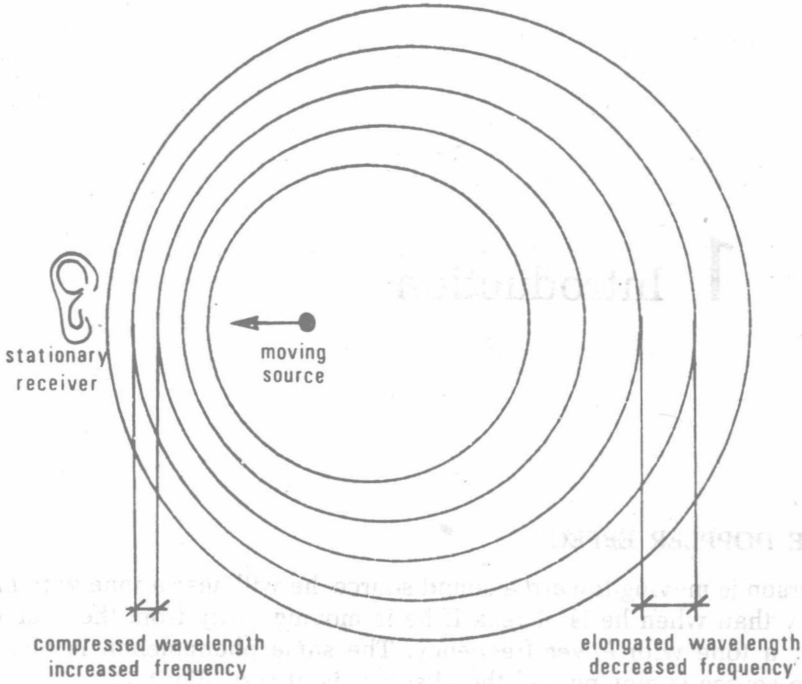

Fig. 1-1. Illustration of the Doppler effect.

sonar. Use of the Doppler shift of ultrasound to measure the velocity of *blood flow* started at about the same time as ultrasonic imaging.[1-3] The earliest application was for qualitative evaluation of peripheral blood flow.[4,5] This technique has also been used together with an inflatable cuff to measure blood pressure[6,7] and is especially valuable for measurement of blood pressure in the legs.[8] When it is used with a servo system for cuff inflation, one may even obtain noninvasive recordings of pressure waveforms.[9] Light and Cross demonstrated the possibility of measuring the blood flow velocity in the aorta.[10]

For all these measurements a **continuous wave** instrument was used. Peronneau and colleagues[11] and Baker[12] later introduced the **pulsed** ultrasonic Doppler instrument, by which the velocity in a small range cell can be studied. This improvement makes it suitable for measurements in the heart because velocities in the different cavities and valve areas can be studied selectively. Scanning the range cell along the ultrasonic beam allows velocity profiles to be obtained. Pulsed instruments developed later give a real-time presentation of time-variable velocity profiles.[13-15]

The main advantage of ultrasonic Doppler techniques is that measurements can be performed noninvasively.[16] Invasive measurements have been made with Doppler transducers mounted at the tip of a catheter,[17] and this technique has been used in measurements of aortic, coronary, and intracardiac blood flow velocities.[18-21] In vascular surgery, measurements have been done directly on vessels.[22-29] This procedure has an advantage over other methods, such as electromagnetic measurements, which require vessel dissection. It has also been used for guidance during vascular surgical procedures in the brain.[30-32] In noninvasive measurements in the heart and larger vessels, an ultrasonic frequency of 1 to 3 MHz can be used. For invasive measurements and for noninvasive measurements in peripheral vessels, 5 to 10 MHz ultrasound has been used. Experiments with 20 MHz ultrasound have been performed.[33]

One disadvantage of the technique has been the problem of quantifying results. This disadvantage has probably precluded a wider clinical application of the method. Holen and co-workers have published a method by which the pressure drop across a flow obstruction can be estimated.[34,35] The basis for this method is that an obstruction produces a marked increase in velocity, as shown for a mitral valve stenosis in Figure 1-2. The increase in velocity requires a

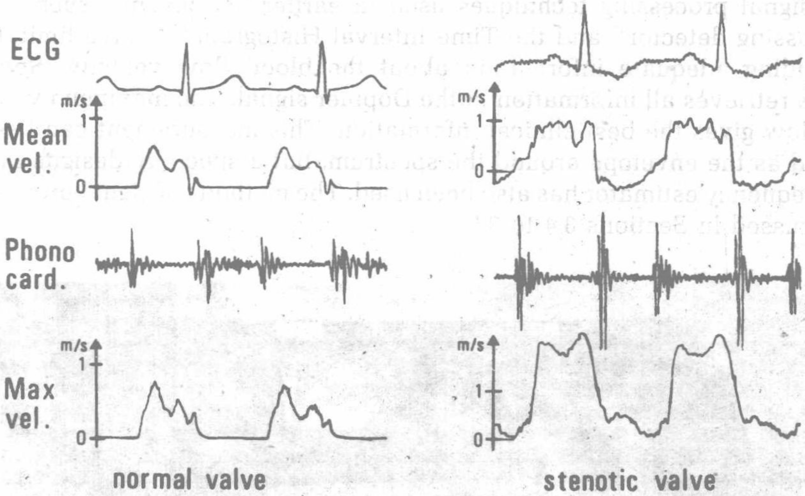

Fig. 1-2. Blood velocity through normal and stenotic mitral valves. Note the increase in velocity in mitral stenosis.

pressure drop that can be obtained from the Bernoulli equation. The method provides valuable information complementary to imaging in the assessment of valvular obstructions and other lesions that produce high-velocity jets, such as valve regurgitations and ventricular septal defects.[36-40] The Doppler effect can also be used for accurate timing of valve opening and closure.[41]

The Doppler shift depends on the angle between the ultrasonic beam and the direction of the blood velocity. This angle is unknown in many situations. For measuring blood velocity through the heart valves, it is often possible to place the transducer so that the angle is small and can be approximated to zero. This situation is necessary to quantify results.

With ultrasonic Doppler methods, blood flow velocity and not volumetric flow rate is detected. The relationship between velocity and volumetric flow rate is discussed in Chapter 2. With a pulsed instrument, the maximum velocity that can be measured is limited because of a phenomenon called **frequency aliasing**. This phenomenon introduces ambiguity in determining the velocity, as discussed in Sections 3.3 and 3.7.

When the velocity limit is exceeded, as often occurs in various heart lesions, high Doppler shifts are mapped onto Doppler shifts with the opposite sign. This phenomenon can indicate a false diagnosis of turbulence, even if the flow is laminar. In the diagnosis of flow disturbances in the heart, turbulence has probably been emphasized too much because even nonturbulent disturbed flow can have a turbulent appearance with existing pulsed instruments.

The continuous wave (CW) instrument does not have this aliasing limitation and can therefore be used to record high velocities in the heart. The lack of range resolution does not usually create problems if one is interested in maximum velocities only. The high velocities can be localized using the pulsed technique. A combined instrument that can be switched from pulsed to continuous mode is therefore useful.

The signal processing techniques used in earlier instruments, such as the zero-crossing detector[42] and the Time Interval Histogram,[43-45] have limitations in providing adequate information about the blood flow velocity. *Spectral analysis* retrieves all information in the Doppler signal. The maximum velocity in the flow gives the best clinical information. This measurement can best be obtained as the envelope around the spectrum, but a specially designed maximum frequency estimator has also been used. The methods of signal processing are discussed in Sections 3.4 to 3.6

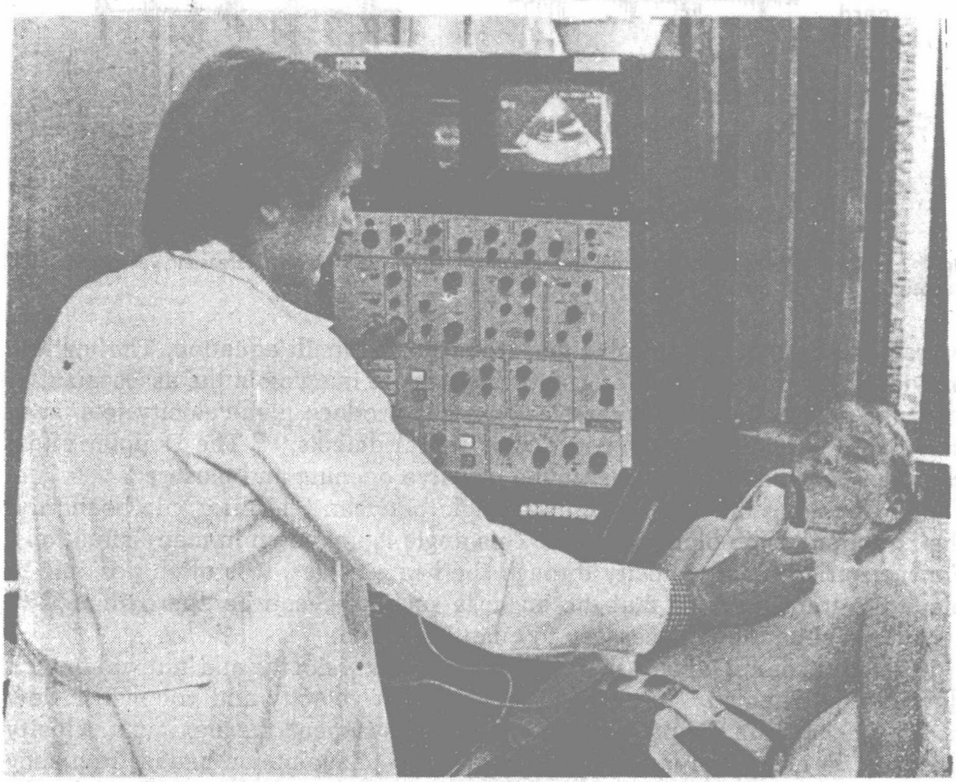

Fig. 1-3. Combined real-time two-dimensional imaging and Doppler instrument (IREX Medical Systems, Ramsey, NJ).

The requirements for optimizing a Doppler system are different from those for optimizing a pulse-echo-amplitude imaging system. Therefore, a separate Doppler instrument can be made more sensitive than one combined with imaging. This topic is discussed in Section 3.8. Moreover, the Doppler signal itself can be used for guidance in localizing the range cell as discussed in Chapter 5, and many of the measurements in this book are done with an independent Doppler instrument.

M-mode was earlier used to guide one to the location of the range cell with pulsed instruments.[43] This method is poor because the transducer positions for Doppler measurements are different from those for standard M-mode examination. For example, for measurements of mitral flow velocity, the beam is pointed from the apex of the heart, in the direction of the flow. For M-mode measurements, the beam is pointed at right angles to the leaflets and the blood velocity direction as illustrated in Figure 3-6.

Two-dimensional imaging gives much better guidance for Doppler measurements than the M-mode method. This imaging is especially useful in patients with complex heart failure, as in some congenital cardiac lesions. Many methods of combining two-dimensional imaging and Doppler measurements suffer

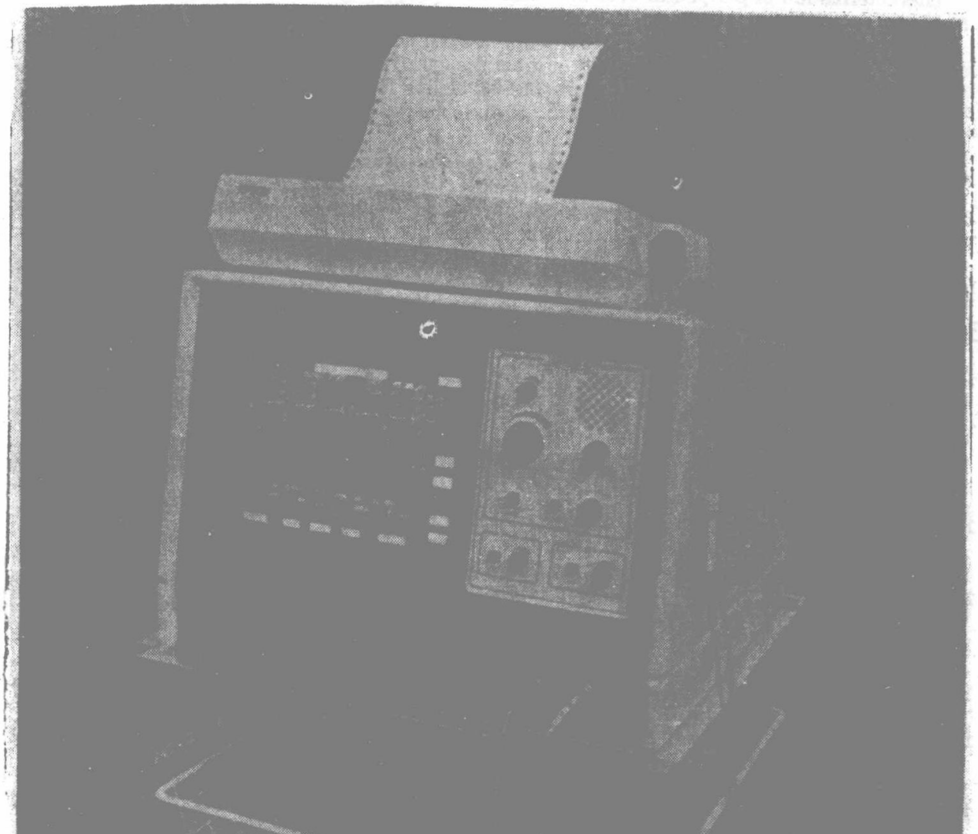

Fig. 1-4. Dedicated Doppler instrument with A-mode and computational capacity to measure cardiac output (Vingmed, Oslo, Norway).

from trade-offs between image and Doppler optimization, by freezing the image, by using a low frame rate of the image, or by reducing the maximum measurable velocity. A new method allows for simultaneous real-time two-dimensional imaging and Doppler measurement without reducing the maximum measurable velocity with pulsed Doppler[46] (Fig. 1-3). One can even do CW Doppler measurements together with a moving two-dimensional image. The Doppler sensitivity is still lower than that obtainable with a dedicated Doppler instrument, however (Fig. 1-4). The best solution is an instrument that allows both separate Doppler measurements and combined real-time two-dimensional imaging and Doppler measurements, as discussed in Section 3.8.

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2 Physics of Blood Flow

2.1 INTRODUCTION

This chapter describes the relationship between blood flow velocity and volumetric flow rate, the concepts of turbulent and laminar flows, and the relationship between the pressure and flow pulse waveforms in the heart and the arteries. These topics provide a background for the way in which disorders in the cardiovascular system affect ultrasonic Doppler measurements. Because this chapter is technical, the reader may prefer to read only the introduction before continuing to other parts of the book.

The *cardiac output*, which is the volume of blood pumped by the heart in a minute, is of special interest for evaluating the capacity of the heart. In the approximation of neglecting the flow in the coronary arteries, this measurement can be obtained from the *volumetric flow rate* of blood in the ascending aorta by integration for one minute. If we integrate the flow rate during systole, we obtain the *cardiac stroke volume.* In aortic regurgitation, integration of the flow rate during diastole gives the *regurgitant volume*. The volumetric flow in peripheral vessels can indicate the capacity of the peripheral arteries for feeding the tissue.

With ultrasonic Doppler techniques, blood *velocities* can be measured. This value is different from the volumetric flow rate of blood. One could say that volumetric flow rate is obtained by multiplying the velocity with the artery cross section, but this statement is an approximation because the velocity of the blood varies across the artery lumen. The velocity as a function of position in the vessel cross section is called the *velocity profile* in the vessel.

If we have a flat velocity profile, that is, if the blood velocity is constant across the lumen, the volumetric flow rate will be exactly equal to the velocity multiplied by the area of the artery lumen. Because the velocity varies across the lumen, we can define an *average velocity* over the artery cross section, $\bar{v}$, so that the volumetric flow rate, q, can be obtained as

$$q(t) = A \cdot \bar{v}(t) \qquad (2.1)$$