DOPPLER ECHOCARDIOGRAPHY

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PREFACE

The purpose of this book is to provide the information necessary to incorporate the Doppler cardiac examination with the echocardiographic examination for individuals who are already able to perform and interpret two-dimensional echocardiography. Using the principles within this text, the reader should be able to make the transition from cardiac imaging to performance and interpretation of Doppler velocity measurements in cardiac chambers and great vessels. Doppler echocardiography requires an additional understanding of physics beyond that necessary for anatomic imaging; we have therefore devoted the second chapter to a nonengineering and principally nonmathematical discussion of Doppler physics. Subsequent chapters describe normal velocity patterns found in cardiac chambers and great vessels and alterations of these patterns that occur in individuals with abnormal circulation. Specific patient examples are analyzed to show how Doppler can be integrated into the practice of cardiology.

Doppler echocardiography began as a qualitative tool for detecting the presence and location of flow disturbances. Although clearly useful for this purpose, the technique did not achieve widespread recognition or implementation until the development of high quality linear rapid spectral analysis. In 1979, microelectronic circuits that provided fast Fourier transforms became available for Doppler echocardiography. This circuitry provided the necessary spectral analysis to allow the beginning of quantitative Doppler echocardiography. To date, Doppler has been demonstrated to allow measurement of outputs distal to the four cardiac valves, and in certain other parts of the circulation, to predict pressure differences across valves with a high degree of certainty. Additionally, Doppler allows approximation of regurgitation volumes, and reasonable estimation of pressures in the pulmonary artery and in other chambers in certain circumstances. To date, hundreds of papers have been published regarding the many uses of Doppler echocardiography and it seemed appropriate at this time to summarize known material in a single volume.

We did not learn Doppler echocardiography in a vacuum. We would like to acknowledge the contributions of many other investigators to our development in this area. An incomplete listing of the individuals to whom we are grateful includes Liv Hatle, David Sahn, Lilliam Valdes-Cruz, Geoffrey Stevenson, Alan Pearlman, Miguel Quinones, Daniel Kalmanson, Walter Henry, Anthony DeMaria, Abdul Abbasi, Julius Gardin, Jose Areias, Donald Baker, James Gessert, James Griffith, and Gary Taylor. We would also like to acknowledge the many hours of work by our students who studied basic Doppler concepts: Zoe Kececioglu-Draelos, Cleo Loeber, Susan Vasko, and Jay Requarth; and our Fellows who investigated clinical aspects: Ehud Grenadier, Demetrio Kosturakis Garcia, Carlos Oliveira Lima, and Jesus Vargas Barron.

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CONTENTS

Chapter 1

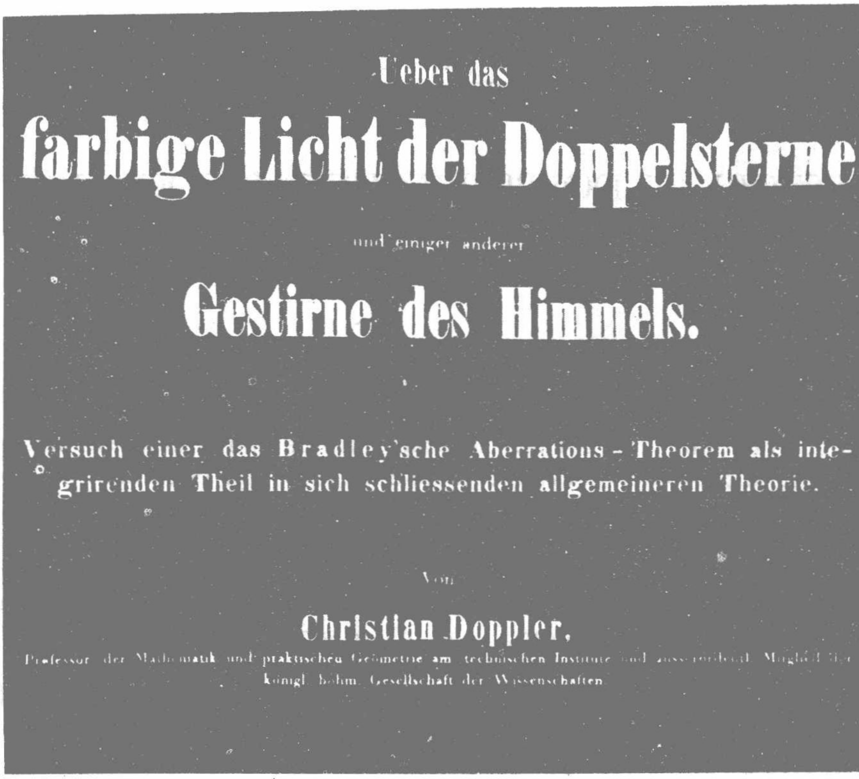
HISTORY OF DOPPLER ECHOCARDIOGRAPHY

The Doppler effect was first described in detail by Christian Johann Doppler in 1842[1] (Fig. 1–1). Dr. Doppler, an Austrian professor of mathematics and geometry, lived from 1803 to 1853. The effect that he described bears his name, and thus "Doppler" is always written with a capital "D." Dr. Doppler applied the principle to shifts in red light from double stars, but not to sound. Changes in light were used to track the motion of celestial objects. The concept that he developed has since been used extensively in astronomy. Later in that same decade, Dr. Bays Ballot applied this principle to sound.

In 1956, Satomura first applied the Doppler technique to detect blood velocity.[2] Application of Doppler ultrasound to cardiology was also attempted a decade later by Lindstrom and Edler, who showed the Doppler frequency spectrum for mitral flow.[3] About the same time, Kalmanson and associates published data regarding catheter velocimetry.[4] For the next several years, continuous wave (CW) Doppler instrumentation was used to detect blood flow in large arteries. Franklin and associates then used continuous wave Doppler for animal studies by implanting transducer and receiver crystals into a cuff that surrounded a blood vessel under evaluation.[5] (Baker, Forster, and Daigle detailed much of the subsequent information.[8]) Later, McCleod used phase shift circuitry and employed a zero crossing frequency meter to allow determination of blood flow direction.[6,7] This device was initially used in experiments on sheep.

Esophageal cannulae with piezoelectric transducers at their tip were independently developed for Doppler work by Baker's group in Washington and by Duck at the University of Newfoundland.[8] These were not successful because of the multiple signals present in the esophagus and because of difficulty in positioning the transducer. This experience, however, led to further placement of transducers in catheter tips,[9,10] which allowed intracardiac evaluation of velocities relative to transducer position.

The next major development was the incorporation of Doppler with



Ueber das

farbige Licht der Doppelsterne

und einiger anderer

Gestirne des Himmels.

Versuch einer das Bradley'sche Aberrations-Theorem als integrirenden Theil in sich schliessenden allgemeineren Theorie.

Von

Christian Doppler,

Professor der Mathematik und praktischen Geometrie am technischen Institute und ausserordentl. Mitglied der

königl. böhm. Gesellschaft der Wissenschaften.

Fig. 1–1. Photographic reproduction of the cover page of Dr. Doppler's article published in 1842.

echocardiography, which required time sharing of pulsed Doppler and pulsed echocardiography. These concepts were developed nearly simultaneously in two independent laboratories, one headed by Baker in Washington,[11,12] and the other headed by Peronneau in France.[13,14] Baker's emphasis was toward transcutaneous blood flow measurement in humans, whereas Peronneau's system was initially used in experiments on animals. In 1972, Johnson and associates published the first American clinical paper regarding the use of Doppler, as developed by Baker, for detecting flow disturbances by audio characteristics.[15] The first commercial pulsed Doppler was combined with an M-mode locator system and released in 1975. Spectral analysis with this system was performed by time interval histography. This system was used by Stevenson and associates to detect specific lesions by interpreting the audio signals.[16] Areias and associates first used the time interval histogram exclusively for diagnosis.[17,18] Goldberg, Allen, Abbasi, Stevenson, Pearlman, and others investigated the clinical usefulness of Doppler diagnosis with this early instrument.[16,19–28]

At the University of Washington, Barker and associates developed instrumentation that allowed the recording of actual velocities and two-dimensional imaging.[29] This combination allowed determination of the site at which velocity was measured and the angle between the flow and the sampling beam. This development made possible true quantitation of blood flow. Later, Moritz and associates developed a "sonic locator system" that provided coordinates for sample volume location relative to real-time imaging.[30] The next major technical advance was Gessert's application of fast Fourier transform (FFT) to spectral displays, which allowed accurate linear analysis of velocity curve profiles.

A major problem with pulsed Doppler echocardiography is inability to measure high velocities. Angelsen and Hatle, from Trondheim, Norway, used continuous wave Doppler to measure these high jet velocities and predict valvar pressure gradients. These authors summarized their findings in the first clinical book written exclusively about Doppler.[31] Almost all subsequent papers dealing with pressure gradient data have been based on one or another concept developed in Trondheim.

Measurement of cardiac output has also had a long history. Light and Cross[32] published a technique in 1972 in which continuous wave Doppler was used to demonstrate that the velocity integral in the aorta related to stroke volume. Pulsed Doppler with alinear spectral analysis was initially used by Magnin and associates to demonstrate the feasibility for measuring aortic flow.[33] Shortly thereafter, Goldberg and co-workers demonstrated that the combination of two-dimensional echocardiography, pulsed Doppler, and spectral analysis by fast Fourier transform was capable of direct measurement of systemic and pulmonary cardiac output.[34]

The history of Doppler echocardiography is still incomplete, but Doppler is now a quantitative clinical diagnostic technique. In the remainder of this text, the physics of Doppler, its instrumentation, and the application of Doppler echocardiography to normal and abnormal states will be presented.

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Chapter 2

DOPPLER PHYSICS

Doppler echocardiography and imaging echocardiography share many properties of physics, but differences also exist. When the echocardiographer looks at a diagnostic image, knowledge of the physics of how that image was obtained is of little importance in most instances. On the other hand, when an examiner looks at a velocity tracing, knowledge of the specific techniques used to obtain that tracing becomes more important. Most cardiologists and technicians do not have an extensive background in physics; thus, the purpose of this chapter is to present a nonmathematical approach to the essential physical concepts of Doppler. We refer readers who wish to delve more deeply into theoretical and mathematical considerations to other publications.[1,2]

FREQUENCY

Frequency defines the number of times an event occurs per unit time. For ultrasound purposes, the unit of frequency is cycles per second, and one cycle/sec = 1 Hertz (Hz). Frequencies presently used in ultrasound range from 1 to 10 megaHertz (MHz) (millions of cycles/sec). These frequencies are far in excess of the audible range, which is from 40 to approximately 15,000 Hz. Doppler ultrasound frequency ranges are similar to those used for imaging echocardiography.

Figure 2–1 demonstrates a sinusoidal waveform. Each cycle begins at zero amplitude, then increases above the baseline to reach a peak, falls through zero to a nadir, and then returns to baseline. To simplify the figures in this chapter, each peak and nadir will be represented by a simple curved line, as shown below the sine wave in Figure 2–1. As frequency increases, the curved lines will be closer together, and as frequency decreases, the curved lines will be farther apart.

TRANSDUCER

Ultrasonic transducers convert pressure into an electrical signal, or an electrical signal into pressure (Fig. 2–2). Transformation between the two states is accomplished with a piezoelectric crystal. The frequency

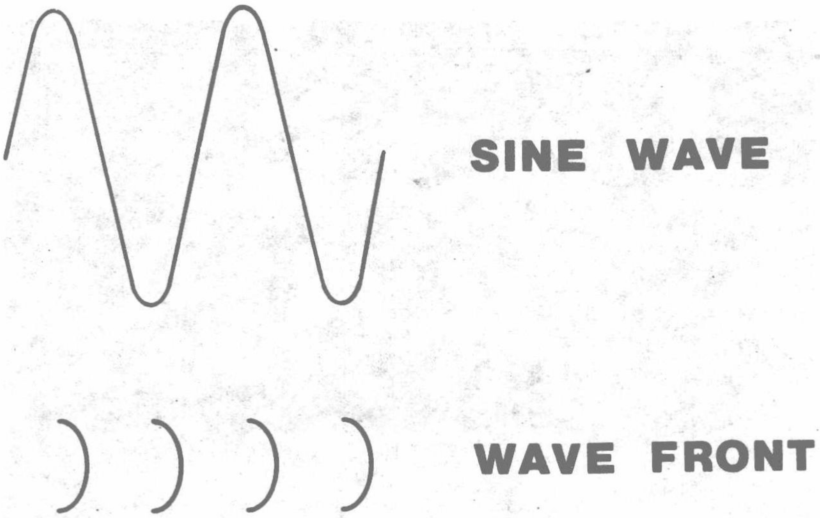

Fig. 2–1. Two cycles of a sine wave. For purposes of illustration, sine waves in the remaining figures will be represented as wavefronts.

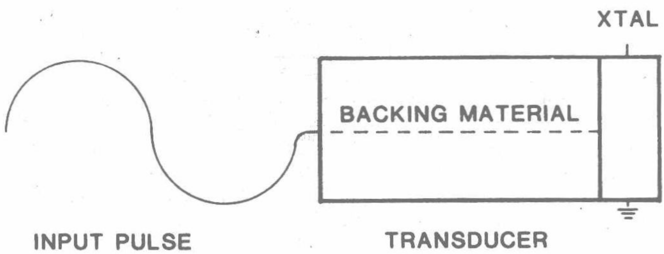

Fig. 2–2. Transducer. An input electrical sine wave is demonstrated. An electrical connection passes to connect to the crystal. Most of the transducer casing is a backing material that is used to absorb the ultrasonic radiation passing toward the casing, and to concentrate most of the ultrasound energy to the face of the crystal.

at which a crystal oscillates is determined principally by its thickness and the material from which it was cut. Oscillation occurs when an electrical signal is imposed upon the crystal. If an oscillating crystal is placed upon a surface, the oscillation of the crystal causes alternating compressions and rarefactions of the molecules of the surface (Fig. 2–3). Each compression and rarefaction represents one cycle. Thus, the electrical signal has been changed into a pressure wavefront that passes through the material on which the crystal was placed. The reverse process is equally important. Pressure wavefronts may be reflected, under certain conditions, from the material, and passed back to the transducer. If the transducer is not transmitting when the reflection returns, it is in a receiving state. When these pressure wavefronts arrive, the crystal