

FINAL REPORT

on

**EVALUATION OF A PULSED
ULTRASONIC DOPPLER FLOWMETER**

Summary of work completed under
NASA Grant NGR 36-008-193
Period: 1 November 1972 to 30 September 1973

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by

**Dr. Michael K. Wells
Assistant Professor of Engineering Mechanics
The Ohio State University**



Introductory Remarks

The work summarized in this report is a result of a collaborative research effort involving individuals from The Ohio State University and the Ames Research Center of NASA and was supported financially by NASA - ARC.

Faculty and staff from several university departments have participated in this interdisciplinary research program and many have contributed their time freely. In addition, the Department of Engineering Mechanics and the Department of Veterinary Physiology and Pharmacology have extensively supported this project in terms of laboratory space, facilities, equipment and released time for research.

The major emphasis of this study was on the in vivo application of the NASA developed pulsed ultrasound Doppler velocity meter (PUDVM) for measuring arterial velocity waveforms. In particular, the performance of the PUDVM was compared with a hot film anemometer of proven accuracy.

The successful implementation of this research program was due in considerable part to the unqualified cooperation of the National Aeronautics and Space Administration. Scientists and engineers at the Ames Research Center have willingly shared with us their knowledge and expertise in ultrasound flowmeter technology and the Center provided us with a prototype pulsed ultrasound Doppler velocity meter and ultrasound transducers.

Contributing Staff

Ohio State University

Michael K. Wells, Ph.D. (Principal Investigator), Assistant Professor of Engineering Mechanics.

Robert M. Nerem, Ph.D. (Consultant), Professor of Aeronautical and Astronautical Engineering.

Robert L. Hamlin, D.V.M. Ph.D. (Consultant), Professor of Veterinary Physiology and Pharmacology.

David R. Gross, D.V.M. M.Sc. (Consultant), Department of Veterinary Physiology and Pharmacology.

John A. Rumberger, Jr. (Ph.D. Student), Department of Aeronautical and Astronautical Engineering.

Gerry L. Geiger, Laboratory Technician, Aeronautical and Astronautical Engineering Laboratory.

NASA - Ames Research Center

Harold Sandler, M.D., Chief, Biomedical Research Branch.

Salvatore A. Rositano, B.S., Research Scientist, Instrumentation Development Branch.

E. Luzzi (NASA Contractor), Owner and Chief Engineer, L and M Electronics, Daley City, CA.

Publications and Presentation (November 1, 1972 - September 30, 1973)

Abstracts

"Comparison of Arterial Velocity Waveforms Using Pulsed Doppler and Hot Film Velocity Meters," by M. K. Wells, P. K. Bhagat and J. A. Rumberger, Digest of the 10th International Conference on Medical and Biological Engineering, Dresden, GDR, 1973, p. 20.

"Coronary Artery Blood Velocity Waveforms Using a Pulsed Doppler Velocity Meter," by M. K. Wells, P. K. Bhagat and D. R. Gross, Proceedings of the 26th Annual Conference on Engineering in Medicine and Biology, Minneapolis, 1973, p. 9-6.

Presentations

"Ultrasonic Techniques in the Measurement of Blood Velocity," by M. K. Wells, Department of Aeronautical and Astronautical Engineering, Aerospace Lecture, Ohio State University, Columbus, November 3, 1972.

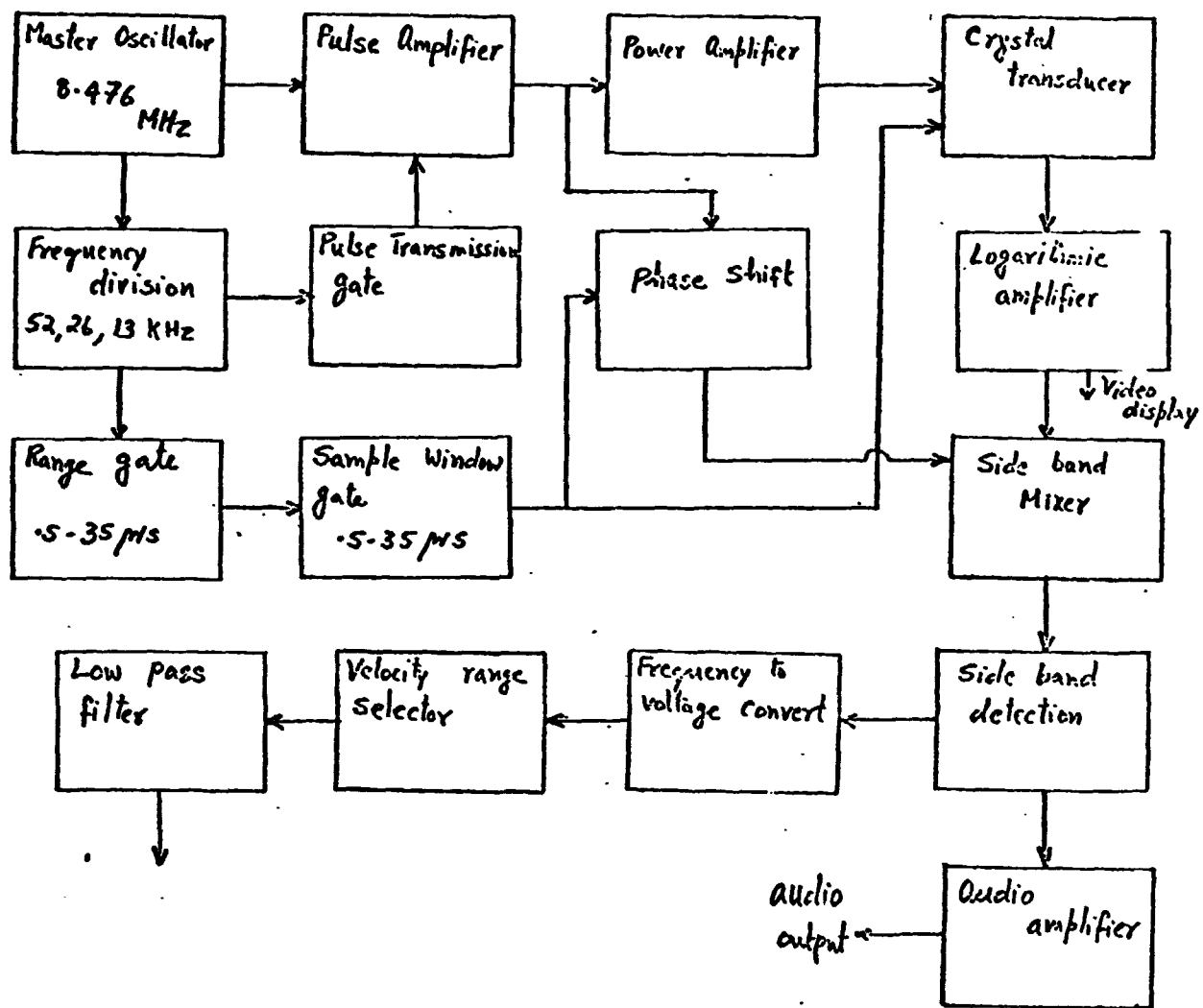
"Noninvasive Measurements," by M. K. Wells, NSF Bio-Fluid Mechanics Conference, Columbus, Ohio, May 3, 1973.

"Comparison of Arterial Velocity Waveforms Using Pulsed Doppler and Hot Film Velocity Meters," by M. K. Wells, Department of Mechanical Engineering Seminar, Colorado State University, Ft. Collins, July 17, 1973.

"Comparison of Arterial Velocity Waveforms Using Pulsed Doppler and Hot Film Velocity Meters," by M. K. Wells, 10th International Conference on Medical and Biological Engineering, Dresden, GDR, August 13, 1973.

I. Pulsed Ultrasound Doppler Velocity Meter

A pulsed ultrasound Doppler velocity meter (PUDVM) developed by the NASA - Ames Research Center was used in this laboratory to measure velocity patterns in blood vessels of experimental animals. The PUDVM measures the velocity of blood cells in a small sample volume within a blood vessel by sensing the change in frequency of backscattered ultrasound. A small piezoelectric transducer emits short bursts of ultrasound into the tissue structure and across blood vessels. Echoes from these structures and from blood cells are received by the transducer during the interval between pulses. The arrival of the backscattered ultrasound at the transducer is delayed in time by an amount proportional to the distance between the transducer and the scatterer while the frequency of the returning ultrasound is altered (Doppler shifted) in proportion to the velocity of the moving particles. By time or range gating the return signal, echoes from targets at specific ranges can be selected. Depth or range resolution is determined by the length of the transmitted pulse, transducer radiation pattern and the gating time. The blood velocity is then determined by mixing the Doppler shifted return signal with two quadrature signals at the emission frequency. Zero crossing detection and phase comparison of the two mixer outputs provides an analog signal proportional to the velocity. Figure 1 shows a functional block diagram of the phase noncoherent pulsed doppler instrument developed by NASA. A tuned oscillator which operates at a frequency of 8.476 MHz serves as the master. Frequency division is performed to select a pulse repetition frequency (PRF) of 52 KHz, 26 KHz or 13 KHz. The pulse repetition



Phase Noncoherent Pulse
Doppler Flowmeter.

Figure 1. Functional block diagram of pulsed ultrasound Doppler velocity meter showing primary elements.

frequency controls an adjustable pulse transmission gate which limits the number of cycles of the master oscillator signal used to drive the piezoelectric crystal transducer. Either 4, 8 or 16 cycles of the oscillator frequency can be selected. This signal is fed to the ultrasonic transducer through a pulse amplifier and a power amplifier. The power supplied to the transducer ranges from 1 to 100 m watts depending on the duty cycle. The crystal transducer acts as a receiver when not being excited by the master oscillator. The pulse repetition frequency also triggers a variable width (.5 to 35 μ s) monostable multivibrator used as a range gate. The trailing edge of the range gate triggers a variable width (.5 to 35 μ s) sample window. The signal from the sample window is gated with the receiver signal to produce an output signal during the sample width. By suitable adjustment of the range gate and the sample window both the depth and sample width of the returned signal may be determined. This returned signal is fed into a logarithmic amplifier which compensates for attenuation of the backscattered ultrasound in the vessel and assures that adequate signal strength is maintained from all range levels. The output of the logarithmic amplifier is used to provide a video display so that the range and sample window information can be observed with the aid of an oscilloscope. The output of the logarithmic amplifier is also mixed with a phase shifted signal derived from the master oscillator. The leading edge of the sample window gate is used for phase synchronization. This mixing using fixed phase shifts leads to the separation of the side bands around the 8.476 MHz carrier so that directional information is preserved. The outputs from the mixer containing the side band information are detected

in two separate but identical detection circuits to provide the audible doppler frequency information. A zero crossing detector is used for frequency to voltage conversion. The highest possible doppler frequency that can be measured using this instrument is 15 KHz which corresponds to a fluid velocity of about 300 cm/sec.

The ultrasound transducers used with the PUDVM were made of single crystals of lead zirconate titanate (PZT-5) 2 to 5 mm in diameter which were imbedded in polystyrene cuffs or bonded to acrylic holders. The cuffs are made in diameter increments of 2 mm to fit snugly around an artery and hold the piezoelectric crystal in a fixed orientation with respect to the blood vessel. The plane of the crystal lies at an angle of 30° to the axis of the vessel and approximately 1 to 2 mm from the vessel's surface. Mechanical coupling of the transducer to the vessel wall is provided by a water soluble gel (Aquasonic) or agar. A cuff transducer is easily calibrated because of the stationary orientation of the crystal to the flow field. On the other hand, the presence of the cuff on an artery may locally alter normal blood velocity patterns.

Transducers of various configurations including half cuffs and pencil type probes were also fabricated in our laboratory. These transducers were required for transcutaneous measurements of blood flow and for transmural applications on veins and other vessels which could not readily accommodate cuff transducers. For example, a half cuff is used to measure flow in coronary arteries since these vessels are imbedded in the heart muscle and their exposure, for the purpose of applying a cuff transducer, involves extensive surgery which most certainly renders the resulting flow nonphysiological. The primary disadvantage of this

type of transducer is that its orientation to the flow axis must be known within precise limits if accurate quantitative determinations of velocity are desired.

The Doppler velocity meter currently being used in our investigations was developed by the Ames Research Center on a design suggested by F. McLeod (NASA grant NGR 05-020-499). The first prototype of this instrument was completed in November 1972 and sent to this laboratory in December by the Ames Research Center on a loan basis. The IUDVM was fully operational in our laboratory in late December, 1972, and the experiments described in this report were conducted between January and June, 1973.

II. Experimental Studies

The pulsed ultrasound Doppler velocity meter was used primarily to measure in vivo blood velocity waveforms in experimental animals. Studies were conducted to compare the quantitative accuracy of the PUDVM with measurements obtained with a hot film anemometer of proven reliability. To date, all reported calibrations of pulsed Doppler velocity detectors are based on comparisons with instruments which measure volumetric flow rate (e.g., electromagnetic flowmeter, CW Doppler flowmeter, timed volume collections, etc.) or upon theoretically predicted velocity profiles in rigid straight pipes. There are no reports comparing the accuracy of pulsed Doppler velocity detectors to measurements obtained with another type of fluid velocity transducer. Our studies provide the first such comparison.

To calibrate the PUDVM and, as a first step toward systematically evaluating its resolution and accuracy for known flow conditions, we assembled a hydraulic model which provides steady laminar flow and varying flow rates in straight circular pipes of several diameters. The system, sketched in Figure 2, consists of a constant head reservoir, test section and outflow reservoir and is equipped with a recirculating pump.

The test fluid is water containing a suspension of silicon particles (Dow Antifoam, 1-1/2% by volume) which simulate the presence of blood cells by providing scattering sites for the ultrasound. This mixture flows through a thin (.001 inch) cellulose tube which has an entrance length to the test section in excess of 100 tube diameters. The cellulose tubing is supported along its length within an acrylic pipe (pipe I.D. = cellulose tube O.D.) except in the test section where the cellulose

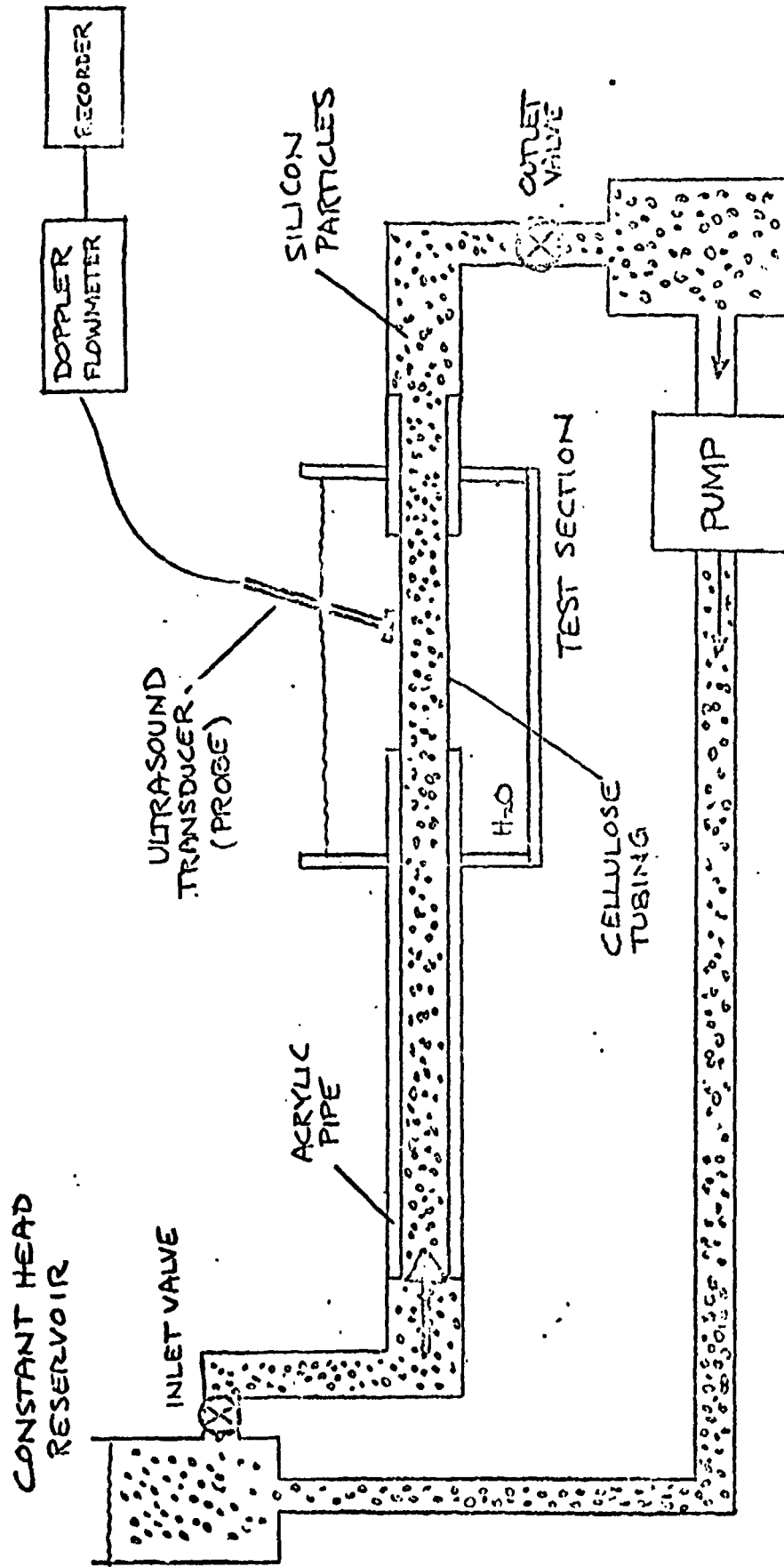


Figure 2. Sketch of hydraulic flow model and apparatus used to calibrate pulsed Doppler flowmeter.

tubing is submerged in a container of water. Cellulose tubing was selected because of its low acoustic impedance. The ultrasound transducer is positioned adjacent to the cellulose tube in the container and beneath the surface of the water which then acts as the coupling medium between the transducer and the simulated vessel.

To evaluate the accuracy of our pulsed Doppler velocity meter for hemodynamic measurements, simultaneous recordings of flow velocities obtained with the PUDVM and a nondirectional hot film anemometer were compared. The constant temperature anemometry system includes a Disa 55D01 anemometer and a 55D10 linearizer. Platinum film sensors mounted on needle probes or on catheter tips were used. A complete description of the hot film velocity meter is included in the Appendix to this report.

In vivo measurements of arterial flow patterns were made in open chest dogs and horses anesthetized with sodium pentobarbital. Figure 3 illustrates a typical experimental setup for simultaneous measurements of velocity in the thoracic aorta using a hot film catheter. In this example the hot film catheter is introduced through a femoral artery and its tip located fluoroscopically in the descending thoracic aorta. In these experiments the catheter tip was not rigidly fixed in the lumen. The ultrasound transducer is positioned adjacent to the aorta at the level of the catheter tip. The ultrasound sample volume can be varied by electronic range gating and for these experiments the sample volume was centered on the axis of the vessel. Arterial pressure is monitored with the aid of a Statham pressure transducer (Model P23BB) coupled to the carotid artery by a saline filled catheter. In experiments using

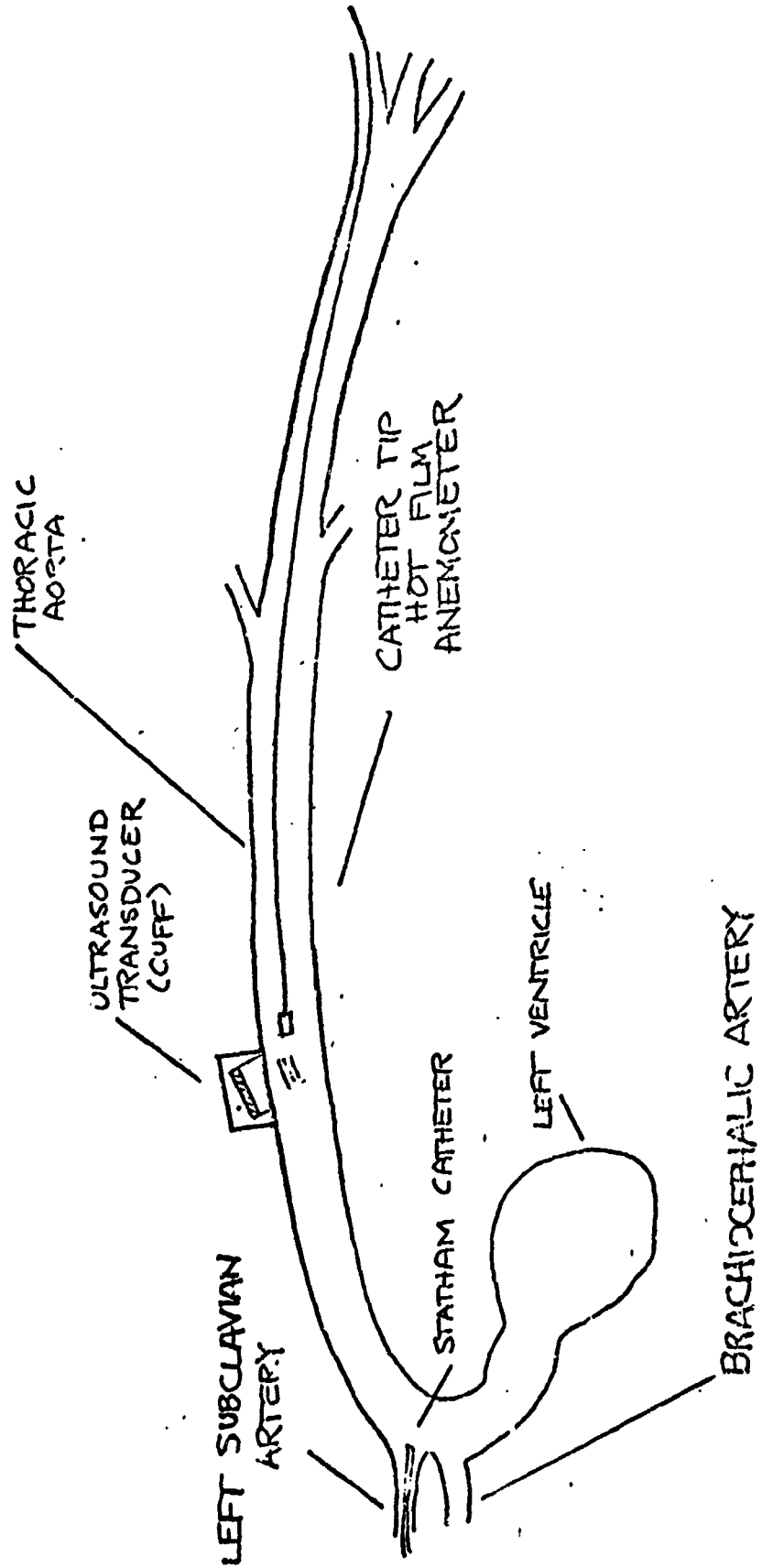


Figure 3. Arrangement of the experimental apparatus used to obtain simultaneous measurements of blood velocity patterns in the canine thoracic aorta.

the rigid needle hot film probe, the probe was inserted into the vessel by direct puncture. In this case the probe was aligned on a diameter normal to the vessel and then fixed to a micrometer to allow for precise placement of the probe tip in the vessel cross section.

III. Experimental Results

A representative recording of centerline velocity waveforms in the canine thoracic aorta is illustrated in Figure 4. A hot film catheter was used in this experiment. Peak velocities of about 70 cm/sec were measured with the PUDVM compared to approximately 80 cm/sec for the hot film. For forward flow the velocity waveforms from both instruments are quite similar although during diastole, reverse flow is evident only on the pulsed Doppler record. Similar recordings were obtained from the horse abdominal aorta as shown in Figure 5. These records were obtained with the PUDVM and "L shaped" hot film probe and again demonstrate a marked similarity in the velocity patterns. Note that both detectors faithfully record the small (approximately 2 cm/sec) velocity perturbations during systole and the large (approximately 15 cm/sec) forward velocity pulse although only the hot film record indicates a disturbance during diastole. This fluctuation in the hot film record may be due to probe motion induced by the pressure wave which propagates down the wall of the aorta.

Figure 6 dramatically illustrates the advantage of making noninvasive measurements of cardiovascular flow parameters. In this example, a measurement of centerline velocity in the horse renal artery was obtained with the aid of the PUDVM with the ultrasound transducer resting on the surface of the renal artery. The transducer was removed and an "L shaped" hot film probe immediately inserted through the vessel wall and positioned with its tip in the center of the artery. Although the first few flow pulses on the hot film record are similar to the PUDVM the blood velocity

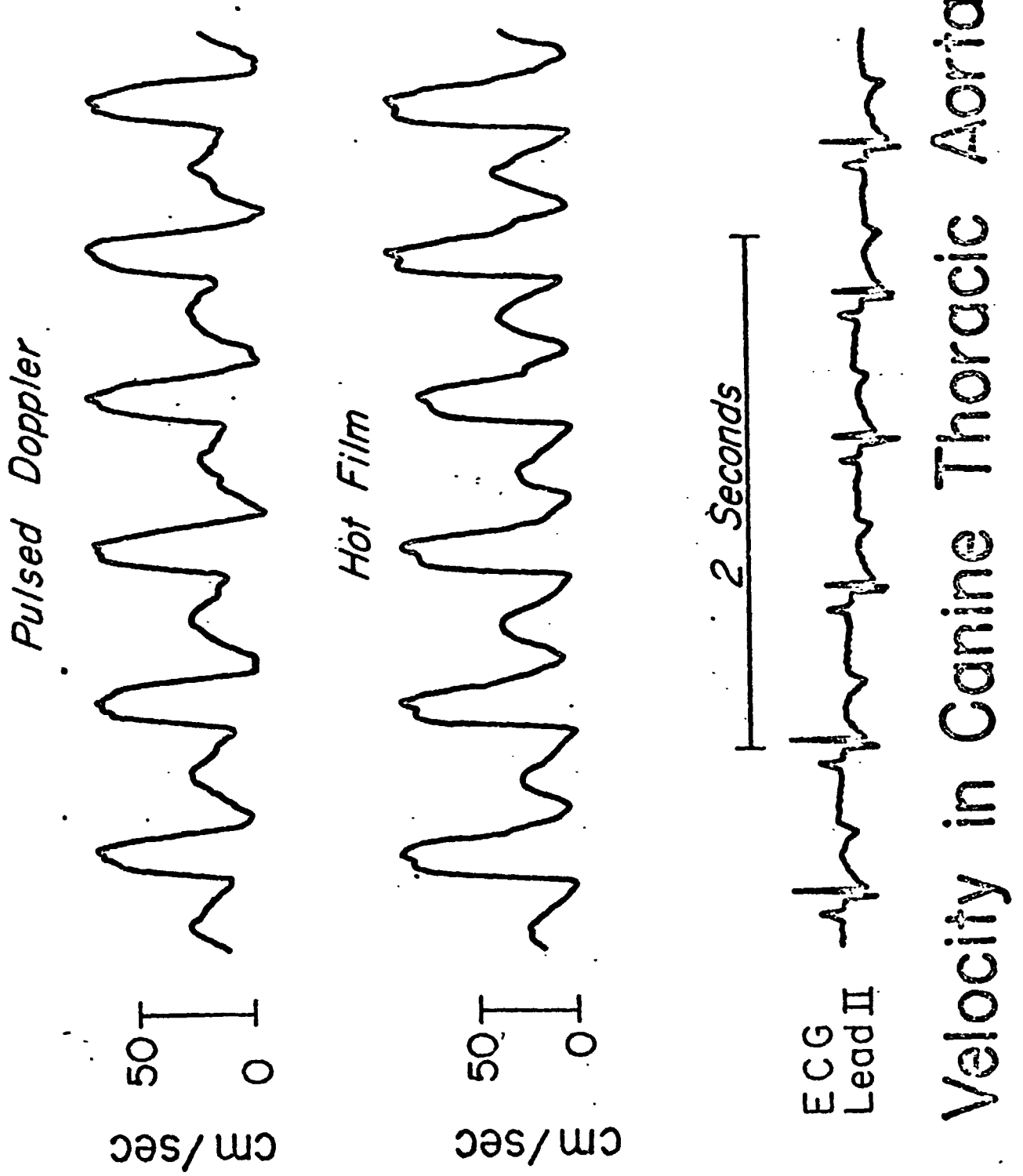


Figure 4. Simultaneous recordings of centerline velocity in descending thoracic aorta of the dog using pulsed Doppler and hot film velocity detectors.

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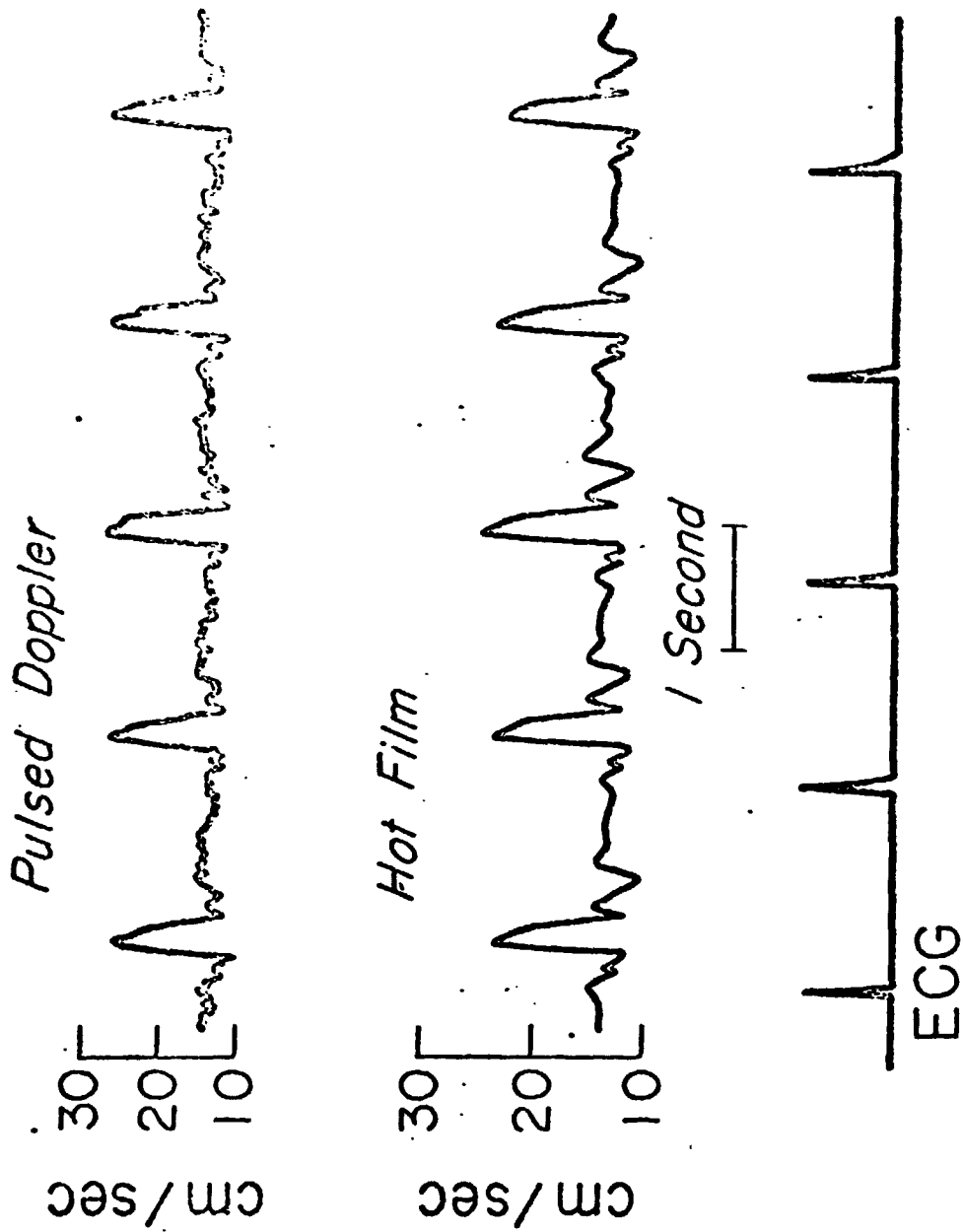
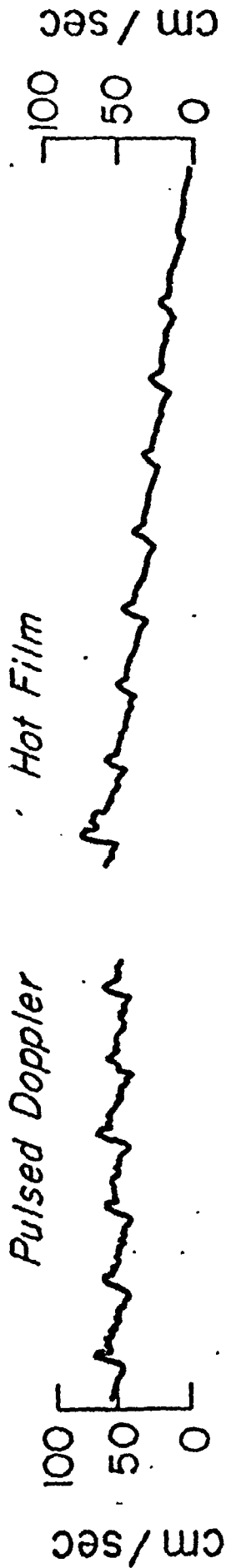


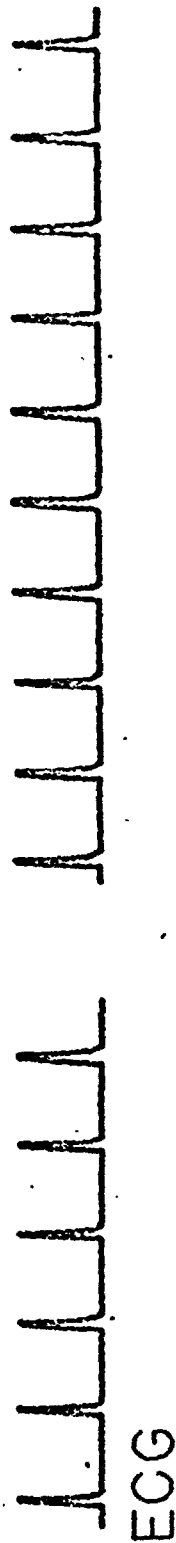
Figure 5. Simultaneous recordings of centerline velocity waveforms from equine abdominal aorta.

Abdominal Aorta Velocity Waveforms (Horse)

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2 Seconds



L. Renal Artery Velocity Waveforms (Horse)

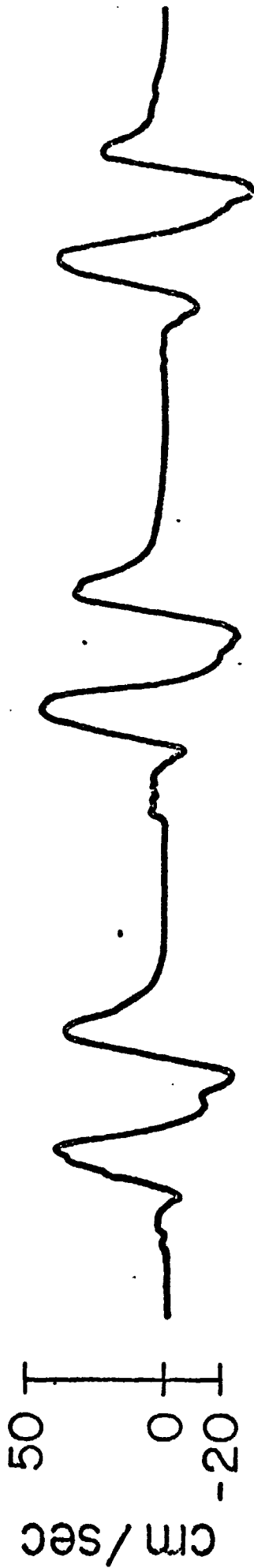
Figure 6. Renal artery velocity patterns measured noninvasively with pulsed Doppler detector and invasively with hot film probe inserted by vessel puncture.

gradually diminishes until there is no longer any flow. This is explained by the fact that the vessel actively responds to the trauma associated with the probe insertion by constricting around the probe until the vessel is fully occluded. It is apparent from this example that invasive measurements of hemodynamic phenomena may not necessarily reflect normal physiological conditions.

In addition to measuring blood velocity in large arteries we initiated studies of velocity waveforms in the coronary arteries of horses. For these experiments we used small ponies (approximate weight 200-300 Kg) which are well suited for these types of measurements because of the relatively large size (3 to 5 mm diameter) of their major coronary branches. Initial results from the left anterior descending branch of the coronary artery are illustrated in Figure 7. The velocity waveform was obtained with the PUDVM and indicates two distinct phases of forward flow and a marked retrograde flow preceding diastole. In this example, the depth of the ultrasound sample volume is approximately equal to the lumen diameter. These waveforms are in contrast to coronary flows measured in dogs and humans with continuous wave Doppler flowmeters or electromagnetic flowmeters which show only a single phase of forward flow. Recordings have been obtained in the right coronary artery with the hot film catheter and these measurements also exhibit the characteristic double waveform and timing of the flow pulses. Figure 8 shows velocity patterns from the horse LAD coronary artery obtained with the PUDVM and hot film anemometer immediately preceding heart failure. Note particularly the single rapid velocity pulse which is indicative of only a small volumetric flow through the vessel. These records were taken at

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LAD Velocity



1 Second



ECG Lead II

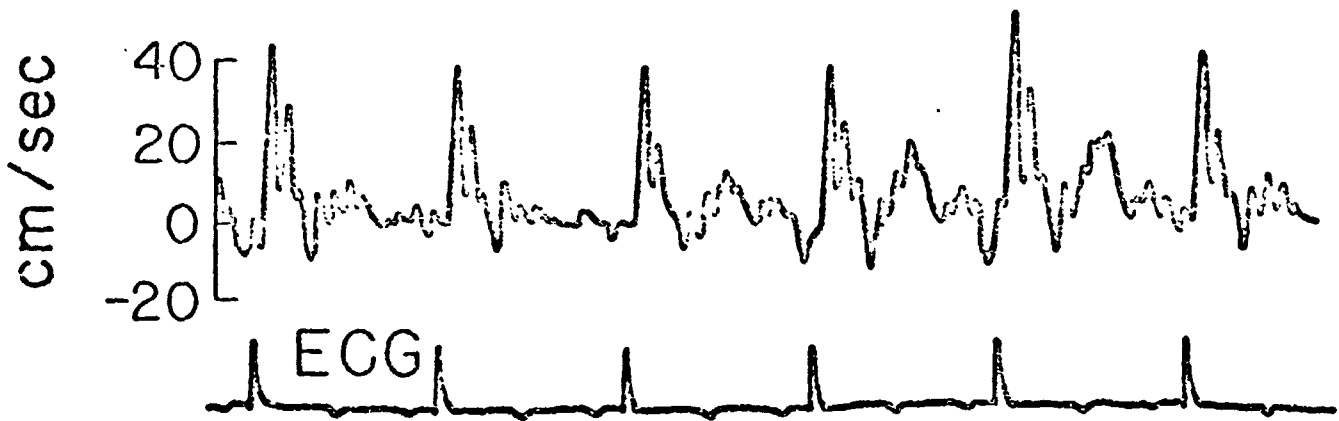
Velocity in Equine Left Coronary Artery

Figure 7. Characteristic velocity waveforms from equine left anterior descending coronary artery obtained with a pulsed Doppler velocity meter.

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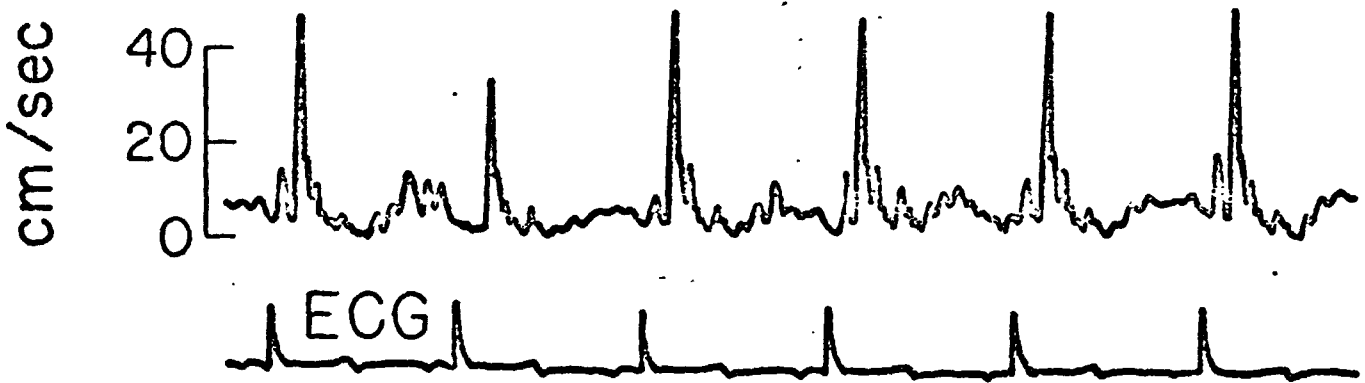
Pulsed Doppler



.1 Second



Hot Film



LAD Coronary Velocity Waveforms (Horse)

Figure 8. Coronary velocity patterns in horse preceding heart failure.

two different times approximately 30 seconds apart. In general the waveforms are similar and the estimates of peak velocity are in close agreement.

APPENDIX

DESCRIPTION OF HOT FILM ANEMOMETER (J. A. Rumberger)

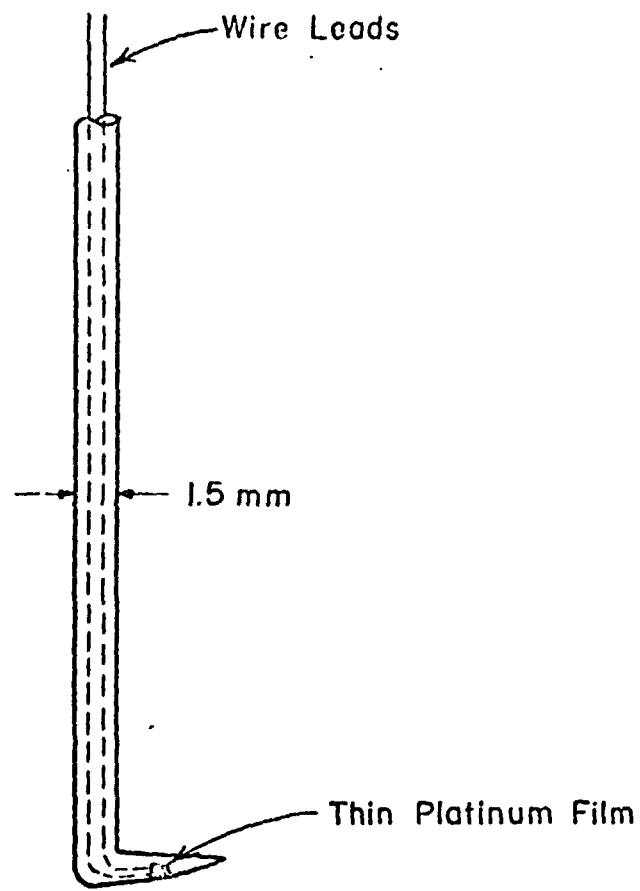
The hot film anemometer system used in this study consists basically of an amplifier and a bridge circuit containing three constant internal resistors and one variable external resistor (i.e., the sensor).

The bridge output signal (non-linearized) is a voltage related to flow properties as follows:

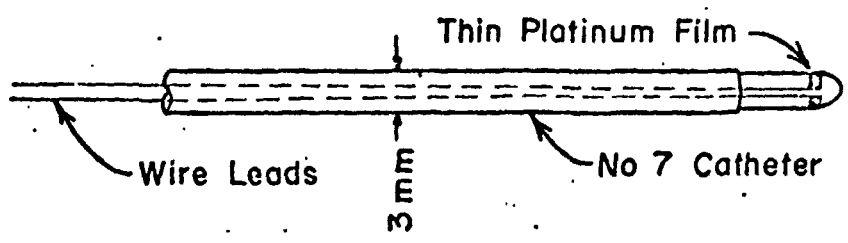
$$V^2 = (A + B(\rho U)^{1/n}) (T_s - T_e),$$

where A, B are constants depending on flow parameters, ρ is the fluid density, U the fluid velocity, T_s the sensor operating temperature, T_e the fluid temperature and n an exponent that varies with the range of velocities expected, the fluid, and the sensor used and is determined experimentally.

The hot film sensor consists of a thin platinum film baked onto a glass rod (2 mm diam) which is maintained at a preset constant temperature ($\sim 5^\circ\text{C}$) above the ambient value of the blood via the anemometer circuitry. Catheter probes and "L shaped" probes were fabricated in our laboratory and are illustrated in Figure A-1. As the velocity past the sensor increases (assuming $\rho = \text{const}$), the sensor surface tends to cool which results in a decrease in resistance. This change in resistance causes the voltage drop across the film to decrease thereby altering the input to the amplifier. The amplifier compensates by increasing current through the sensor in an attempt to balance the bridge. The resulting voltage drop across the bridge is monitored at the bridge output and is a direct



L-Shape Hot Film Probe



Catheter Hot Film Probe

Figure A-1. Sketch of catheter and "L-shape" hot film probes used to monitor velocity waveforms in blood vessels.

reflection of the velocity of the fluid media past the sensor surface.

A commercially available anemometry system was used for the experiments and consisted of a Disa 55D01 anemometer and a Disa 55D10 linearizer.

The hot film sensor was calibrated with the aid of a tri-channeled plexiglass dish mounted on a variable speed turntable. Steady calibration speeds from 0 cm/sec to 150 cm/sec were available. During calibration, the blood (or water) is maintained at 38°C by means of circulating water between the inner and outer channels of the dish.