port literature generated in such voluminous quantities as a result of government-financed programs in science and technology.

The symposium concluded with a statement of the importance of the problem from the viewpoint of the national interest, presented by Julius N. Cahn (director of the Medical Research project of Senator Humphrey's Subcommittee on Reorganization of the United States Senate Committee on Government Operations). Cahn underlined the importance with which the government views the information problem and its vital interactions with the health and welfare of the nation. With the real understanding exhibited by the Senate Committee and its appreciation of the problems before the scientific community, the outcome of the Committee studies may be expected to provide a continuing impetus for greater accomplishment by the scientific community.

The symposium was outstanding in the sense that the audience it attracted contained predominantly working scientists rather than professional documentalists, information specialists, or librarians. Effective progress in battling the "exploding literature" can only be attained to the extent that the working scientist is aware of the problem and appreciative of the necessity for taking effective steps to overcome it. Any forum, therefore, which brings the problem to the working scientist and enlists his sympathetic understanding represents an important contribution to the attainment of better solutions.

The papers presented at the symposium will be published later this year in *Federation Proceedings*.

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Blood Flow

Physiologists, engineers, mathematicians, and physicists from the United States and seven foreign countries attended the first international symposium on pulsatile blood flow which was held at the Presbyterian Hospital in Philadelphia, 11 to 13 April. Recent progress in the dynamic analysis of blood flow was reviewed, the present state of our knowledge of the field was re-evaluated, and the existing problems and their possible solutions were outlined.

The transducer recording systems used for accurate evaluation of pulsatile flow must meet considerably higher requirements than those which are generally considered satisfactory. A flat frequency response from 0 to 30 cycles per second is absolutely necessary. The present state of manometry and displacement measuring devices is probably adequate provided extensive care is exercised both for their static and dynamic calibration. The damaging effects of minute air bubbles on manometer behavior are still not generally realized.

The performance of flow-metering devices, on the other hand, is far from satisfactory. Two main problems must be solved before either the electromagnetic or the ultrasonic flowmeter can be used with confidence for such studies. Although the calibration of electrical performance can be carried out with relative ease, the dynamic calibration of the whole electromechanical system is fraught with difficulties. Adequate volume displacements at the required frequencies necessitate powerful pumps, the output of which must be exactly known. Although such devices can be built, they are likely to be considerably more expensive than the flowmeters themselves.

The second problem relates to our ignorance about the distribution of velocity profiles in various types of flows and cross sections. Theoretical considerations indicate that errors of up to 25 percent may be introduced if the velocity profile used for the calibration is significantly different from the profiles actually encountered during the experimental measurement. Additional questions which are at present not too well understood include the effects of hematocrit, wall thickness, temperature, blood chemistry (ionization), vessel fit, field frequency and wave shape, electrode character, and contact potential upon flowmeter performance.

Since minor errors in amplitude and phase lead to significant differences in some of the calculated parameters, a better understanding of these effects is essential for a reliable interpretation of observed results. Considerably more theoretical and experimental work is necessary before these effects can be properly evaluated.

Theoretical and experimental approaches to pulsatile flow have shown that blood flow through the vascular bed depends only upon two parameters, the driving pressure and the impedance of blood and vasculature. The driving pressure is, of course, provided by the pumping action of the ventricles, so that the impedance describes the overall behavior of the vascular bed and its content and includes explicitly the inertial and viscous properties of the fluid as well as the physical characteristics of the vessel wall. A theoretical analysis of this behavior was carried out by Womersley only a few years ago, and experimental results presented at this meeting indicate that Womersley's theory underestimates the frictional losses in pulsatile flow. These differences may result from the fact that the individual vessels taper, that turbulence is present during at least part of the cardiac cycle, and that the vessel wall is viscoelastic. A powerful analysis of the tapering effect was presented.

While this approach is very promising, a number of refinements are necessary until the predictions resulting from this theory are as good as those obtained from Womersley's work. In uniform, elastic tubes, the pressure flow behavior can be predicted by classical theory. As soon as nonuniformities such as changes in wall thickness, vessel diameter, or branching are introduced the observed results become quite different from those expected from theory, even in relatively simple models. The nonuniformity of the vascular tree is not limited to geometrical factors alone; it also includes progressive stiffening of the vascular wall toward the periphery. There are significant species differences: the Windkessel might be an appropriate model for the domestic turkey but quite unsatisfactory for mammals. Few quantitative data on the behavior of smooth vascular muscle are available at present, but its influence upon the physical properties of the vessel wall may account for an increased pressure wave transmission in the smaller blood vessels.

The blood flow through the vessel wall is another factor which has been neglected until recently even though it is well known that coronary blood flow changes widely from cardiac systole to disatole. Similar effects may be expected in the arterial wall and may result in variations of its mechanical behavior. Model experiments in tubes with circular and elliptic cross sections indicate that even minor deviations from a circular cross section may introduce serious inequalities in the distention of viscoelastic tubes. These inequalities reach a maximum in the ellipse where the two semiaxes change in opposite direction during the pulsatile cycle. Further investigation is necessary to determine how far these results apply to various vessels *in situ.*

In hydrodynamics the Reynolds number defines the ratio between inertial and viscous forces and its critical value, a condition which is necessary to maintain turbulence. This condition can, however, only be evaluated if the flow channel is long with respect to its hydraulic depth. In the vascular bed this ratio is quite small, and it is therefore of minor importance if the introduced disturbances maintain themselves or die out after having traveled a certain distance, since new disturbances will already have been introduced over this interval. Birefringence studies indicate that, in pulsatile flow, turbulence in tubes of the size of the larger vessels appears already at mean velocities of 20 to 30 centimeters per second—that is, values which are certainly exceeded over most of the systolic part of the cycle. Additional turbulence is introduced at any branch point.

Measurements of pressure gradients at these flow rates in distensible tubes indicate that the turbulence observed by the birefringence technique may alter the pressure-flow relations considerably. The production of turbulent flow in pulsatile flow depends not only on the hydraulic depth, kinematic viscosity, and mean velocity, but also on the frequency and amplitude of the superimposed oscillations and on the physical properties of the wall. For an evaluation of the latter, the shape of the actual cross section has to be considered.

These problems are as much of a challenge to the mechanical engineer and hydrodynamicist as to the vascular physiologist. Powerful methods are available for study, but requirements exist not only for exquisite instrumentation and extensive computer facilities, but also for multidisciplinary manpower.

This symposium has been another demonstration of the advantages in combining several disciplines into one team, provided the problem is properly defined. It was supported by grant HE 07692-01 from the National Institutes of Health. The proceedings will be published this fall by the McGraw-Hill Book Company.

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