THE VISCOUS NATURE OF BLOOD FLOW IN CAPILLARY TUBES

by

Donald Wesley Rennie, B.S.

A THESIS

Presented to the Department of Physiology
and the Graduate Division of the University of Oregon Medical School
in partial fulfillment
of the requirements for the degree of
Master of Science

May 1952

APPROVED:

[redacted]

.....

(Professor in Charge of Thesis)

[redacted]

.....

(Chairman, Graduate Council)

TABLE OF CONTENTS

INTRODUCTION 1

REVIEW OF LITERATURE 9

METHODS 24

A. Constant Flow Technique 25

B. Constant Pressure Technique 36

RESULTS 40

A. The Law of Pressures 40

B. The Law of Diameters 88

C. The Law of Hematocrit 94

DISCUSSION 96

SUMMARY 100

BIBLIOGRAPHY 102

LIST OF FIGURES AND PLATES

Figure 1. Constant Flow Apparatus 26

Figure 2. Constant Pressure Apparatus 37

Figure 3. Design of Special Capillary Tube 63

Plate 1. Stroboscopic Picture of Blood Flow in Capillary Tube 73

LIST OF CHARTS

Chart 1. Pressure-flow graph for water in tubes which are too short for the application of Poiseuille's Law 14

Chart 2. Volume ejection curves for the hypodermic syringes used in the constant flow apparatus 27,28

Chart 3. Maximum pressure limit of the Sanborn electromanometer 33

Chart 4. Pressure-flow graphs for water obtained in both the constant flow apparatus and the constant pressure apparatus 34

Chart 5. Pressure-flow graphs for water and blood in a 508 micron metal tube at 20°C. (high velocity).. 45,46,47

Chart 6. Pressure-flow graphs for water and blood in a 250 micron metal tube at 37°C. (high velocity)..... 50,51

Chart 7. Pressure-flow graphs for water and blood in a 250 micron metal tube at 37°C. (low velocity) 53

Chart 8. Pressure-flow graphs for water and blood in a 200 micron metal tube at 37°C. (low velocity) 55

Chart 9. Pressure-flow graphs for water and blood in a 581 micron glass tube at 37°C. (high velocity) 57

Chart 10. Pressure-flow graphs for water and blood in a 338 micron glass tube at 35°C. (high and low velocity) 59,60

Chart 11. Pressure-flow graph for water and blood in a 95 micron glass tube at 36°C. (low velocity) 64,65

Chart 12. Pressure-flow graphs for water and blood in a 105-110 micron glass tube at 37°C. (low velocity) 67,68

Chart 13. Pressure-flow graphs for water and blood in a 140-162 micron glass tube at 37°C. (low velocity) 70,71

Chart 14. Pressure-flow graph for water and blood in a 404 micron glass tube at 35°C. (low velocity) 77

Chart 15. Pressure-flow graph for water and blood in a 338 micron glass tube at 35°C. (low velocity) 79,80

Chart 16. Pressure-flow graph for water and blood in a 309 micron glass tube at 35°C. (low velocity) 82

Chart 17. Pressure-flow graph for water and blood in a 309 micron glass tube at 35°C. (high velocity) 84

Chart 18. Pressure-flow graph for water and blood in a 250 micron metal tube at 35°C. (high velocity) 86

Chart 19. Plot of volumetric rate of flow as a function of tubular diameter for water and blood. Pressure head constant. 90

Chart 20. Plot of pressure gradient as a function of tubular diameter for aqueous glycerol and blood. Volumetric rate of flow constant. 92

Chart 21. Plot of blood specific viscosity as a function of hematocrit. 95

INTRODUCTION

An enigma characterizes the concept of blood viscosity at the present time, since several investigators have demonstrated an anomalous behavior of blood flow under certain dynamic conditions. Significant deviations of the viscosity coefficient of a single blood sample have been reported in such instances. The flow conditions at which these anomalous changes occur are precisely those which would be predicted in the peripheral vascular bed, where any aberrant alterations in blood viscosity would be of significance to the organism. For instance, it has been demonstrated that under low pressure heads of flow (low linear velocity) blood exhibits an unusually high specific viscosity. It is in the peripheral vascular bed that the linear velocity of blood flow is slowest, and if this factor is of importance one would anticipate a disproportionately high viscous resistance in this region. It has also been observed that a blood sample flowing through a capillary tube will undergo a decrease in its specific viscosity in tubes under 0.3 mm. in diameter.(1) This observation is generally accepted by physiologists, and the phenomenon is cited as an economy to the organism, since viscous resistance is appreciably reduced from what it would be if this did not occur. Unfortunately, the velocities of flow employed were not measured, but there is presumptive evidence that they were high. The establishment of physiologic velocities of flow in such narrow tubes may influence the magnitude of blood viscosity. Such information would be of more physiologic significance than any which exists at the present time.

The objective of this study is to determine the behavior of blood flow in single cylindrical capillary tubes, with emphasis on the changes in whole blood viscosity which occur in each tube when the linear velocity of flow duplicates as nearly as possible that which may exist in individual blood vessels of similar diameter.

Theoretic basis of viscous flow. When pressure is applied to one end of a fluid mass contained in a horizontal tubular conduit, motion is established which will immediately cease if the pressure is withdrawn. If a constant pressure is sustained, a state of uniform fluid motion will result in which all the liquid particles move at a constant velocity relative to one another and in a path parallel to the axis of the tube. This is known as laminar flow.

Since the maintenance of laminar flow in a cylindrical tube depends upon an applied external force, this system must present a continual impedance to flow requiring energy expenditure to overcome. Two possible sources of this impedance may exist in the system described. There is a fluid-solid interface at the inner wall of the tube, and it is conceivable that the resistance to flow may be concentrated on this area. It was first shown by Coulomb[2] in 1798 that the physical nature of the solid had no influence on the magnitude of this resistance, and it is accepted at the present time that those surfaces which are 'wet' by a fluid substance bind a molecular layer of the fluid and that the linear velocity of this monomolecular film is zero.

The other source of resistance could be within the fluid mass itself, arising from mutual interference of the molecules of the liquid. Isaac Newton(3) was the first to state this concept of intrafluid or viscous resistance. He recognized that a continuous external force must be exerted upon a fluid to maintain uniform velocity of motion. Furthermore, he observed that motion imparted to one portion of a fluid mass tended to be propagated to the entire mass, and he attributed these phenomena to a 'lack of slipperiness' between particles of the liquid. It is this lack of slipperiness which is termed the viscosity of a fluid.

There is an apparent analogy between viscosity and solid friction but this is more obvious than real. Solid friction is independent of the velocity with which two solid objects slide past one another and of the area in contact. It is determined solely by the force existing between the two objects at right angles to the direction of motion. A constant pressure applied to one solid object will cause, not uniform velocity of motion, but uniform acceleration of motion with respect to another.

The magnitude of viscous resistance, on the other hand, is directly proportional to the velocity with which two fluid particles move with respect to one another (the velocity gradient). It is directly proportional to the area of contiguous fluid surfaces, inversely proportional to the thickness of the fluid film and independent of the force exerted at right angles to the axis of flow;

therefore it differs from solid friction in all respects except that both represent a force acting to oppose motion.

The viscosity of a fluid may be defined as that property by which it tends to resist deformation and flow. It is manifest as a finite force arising within the moving fluid mass and acting as a shear stress between contiguous fluid lamellae. Its direction of action will be in the opposite direction to that of flow, and its magnitude will be directly proportional to the linear velocity of flow. When uniform laminar flow occurs, the force tending to maintain flow will be exactly balanced by the viscous resistance within the fluid, regardless of the physical nature of the tubular conduit.

Because the viscosity of a fluid is dependent upon the velocity gradients between contiguous fluid lamellae and is therefore continually varying with different flow rates, it does not serve as a useful concept. However, by using the viscosity concept as a basic postulate, it is possible to define a property of viscous fluids which does have a practical meaning. This property is the viscosity coefficient. As the word coefficient implies, it is a ratio. It is the ratio of shear stress developed within a moving fluid mass to the velocity of flow.

$$\eta = \frac{\tau}{\Delta V} \qquad \ldots\ldots\ldots (1)$$

τ = shear stress

ΔV = velocity gradient

According to the basic concept of viscosity, this ratio is always a constant for a given viscous fluid.

The viscosity coefficient may be defined as the force necessary to create a unit velocity gradient between two fluid lamellae of unit area separated from one another by a contiguous fluid phase of unit thickness.

$$\eta = \frac{\text{Force X Thickness}}{\text{Area X Velocity}}$$

In the C. G. S. system, this is represented as,

$$\eta = \frac{\text{Dynes X Cm X Sec}}{\text{Cm}^2 \text{ X Cm}} = \frac{\text{Dyne-Sec}}{\text{Cm}^2}$$

One such unit is called a poise. Water at 20°C. has a viscosity coefficient of approximately one centipoise (1/100 poise). The C. G. S. system is cumbersome for many individuals to use, particularly those engaged in research on blood viscosity. It is easier to visualise a ratio of the viscosity coefficient of blood to that of water, and such a ratio is termed the specific viscosity of blood.

Utilizing the concept of viscous flow outlined above, a mathematical deduction of the volume of flow per unit of time through a cylindrical tube was made in 1856 by Wiedemann[4] and in 1860 by Hagenbach[5]. Working independently of each other, they both arrived at the same equation, which has become known as Poiseuille's Law in honor of the French physician and researcher who contributed exact experimental data on the flow of water in narrow cylindrical tubes. The mathematical deductions agree entirely with his empirical data, collected from 1830 to 1852, and place the concepts of viscous laminar flow on a firm foundation.

Poiseuille's Law for flow in a cylindrical tube:

$$Q = \frac{\pi R^4 \cdot P}{8 \eta L} \qquad \ldots\ldots (2)$$

expresses volume flow per unit time, Q, as a function of the radius, R, of the tube; the length, L, of the tube; the drop in lateral pressure, P, across L and the viscosity coefficient, η, of the liquid. It should be re-emphasized that this Law is based on the assumption of viscous laminar flow. The above variables influence volumetric rate of flow only insofar as they effect total viscous resistance in this flow system.

Using this expression, it is possible to measure the viscosity coefficient of a liquid in a capillary tube:

$$\eta = \frac{\pi R^4 \cdot P}{8 Q L} \qquad \ldots\ldots (3)$$

It is by substitution in this formula that the viscosity coefficient of water has been calculated from the precise data of Poiseuille.

Since the variables R and L are particularly difficult to measure in capillary tubes, it is customary to compare water flow with the flow of blood <u>in the same tube</u>. The factor, R^4/L, thus becomes a constant for the purpose of comparison and may be combined with the constant, $\pi/8$, to give a single constant, K.

The viscosity coefficient of water, η_w, may now be expressed:

$$\eta w = K \cdot \frac{Pw}{Qw} \qquad \ldots\ldots (4)$$

Pw = pressure head for water flow

Qw = volume flow of water in unit time

and a similar expression may be set up for the viscosity coefficient of blood, η_b , in the same capillary tube:

$$\eta_b = K \cdot \frac{P_b}{Q_b} \qquad \ldots\ldots (5)$$

P_b = pressure head for blood flow

Q_b = volume flow of blood in unit time

If a constant pressure head is used in each instance ($P_w = P_b$) the ratio of blood viscosity coefficient to water viscosity coefficient (specific viscosity of blood) may be expressed:

$$\frac{\eta_b}{\eta_w} = \frac{K \cdot \frac{P_b}{Q_b}}{K \cdot \frac{P_w}{Q_w}} = \frac{Q_w}{Q_b} \qquad \ldots\ldots (6)$$

On the other hand, a constant volumetric rate of flow may be established in each instance ($Q_w = Q_b$), in which case the specific viscosity of blood may be expressed:

$$\frac{\eta_b}{\eta_w} = \frac{K \cdot \frac{P_b}{Q_b}}{K \cdot \frac{P_b}{Q_b}} = \frac{P_b}{P_w} \qquad \ldots\ldots (7)$$

That is, the specific viscosity of blood is simply a ratio of water flow to blood flow if pressure head is held constant, or the ratio of blood pressure head to water pressure head if volumetric flow is held constant between two consecutive determinations.

Although other methods exist for measuring the viscosity coefficients of fluids, the cylindrical capillary tube approximates physiologic conditions of flow most closely and has been almost universally adopted for blood viscosity determinations. For purposes of this investigation, no other methods need be described.

Review of the Literature

From the foregoing sketch it can be seen that the theoretical aspects of laminar flow reached their present accepted form by 1860 with the deductions of Hagenbach and Wiedemann. The basic concepts of fluid viscosity, however, must be credited to Newton, 150 years earlier. In the early part of this interim a large body of experimental data on water flow had accumulated, contributed mostly by French hydraulic engineers. Because of their preoccupation with industrial problems, most of their work involved flow in conduits whose dimensions are not applicable to the vascular bed. The results obtained in these larger tubes differ from those which would be predicted from Poiseuille's Law for reasons that are beyond the scope of the present discussion.

The first experimental data to support Hagenbach's hypothetical formula were supplied by 1839 by Hagen.(6) Three brass tubes were used of 2.54, 4.14, and 5.88 mm. diameters. Water flow was tested at different temperatures and under different pressure heads. The volumetric rate of flow was determined by weighing the efflux over a given period of time. According to this data,

$$Q = K \frac{PR^{4.2}}{L} \qquad \ldots\ldots (8)$$

where the symbols have the same meaning as in formula (2). He suggested that the true value of the radius exponent was four. This work, although brief and inexact, represents the first empirical confirmation of the mathematical laws of laminar flow which were soon to

be developed.

Poiseuille's elaborate experiments during the ensuing twenty years were to add a polish to this phase of flow in narrow tubes which has not dimmed in 120 years. Poiseuille[7], working as a physician and a medical researcher, approached the problem of capillary flow from a physiologic aspect. He was anxious to deal with tubes whose diameters were in the range of actual blood vessels and used glass capillary tubes whose exact dimensions could be measured under a microscope. From a large number of tubes, seven were finally selected on the basis of their uniform bore and circular cross section. These tubes varied in diameter from 0.65 mm. to 0.015 mm., five of them being less than 0.2 mm. in diameter. Each tube was fused at one end to a calibrated reservoir, and the flow volume per unit time was determined by timing the meniscus past two scratch marks on this reservoir. As a source of pressure head he used compressed air in a 60 liter copper chamber protected from temperature change. Pressure was recorded with either a mercury or water manometer.

Flow in each tube was exhaustively studied over a wide pressure and temperature range. A distal fragment from each tube was then removed and flow again studied in the shortened tube, thus introducing the variable of length into the investigation while keeping diameter constant. The fluid which he studied in greatest detail was water, although mercury and alcohol-water mixtures also were tested. A single attempt was made to study the flow of ox blood in his apparatus,

but clotting and other technical difficulties prevented him from pursuing this further.

Poiseuille's observations led him to formulate three laws of flow in narrow capillary tubes:

1. Law of Pressures. In the same tube, the volumetric rate of flow is proportional to the pressure gradient, providing that a certain minimal tubular length is exceeded, which increases with the radius.
2. Law of Diameters. The volumetric rates of flow through two tubes, all other variables being equal, are related to each other as the fourth power of the diameters.
3. Law of Length. In the same tube, the volumetric rate of flow is inversely proportional to the length of the tube, providing that the length exceeds the critical minimal value referred to in the Law of Pressures.

In addition, the volumetric rate of flow was seen to be greatly augmented by increasing the temperature of flow, and the influence of temperature on flow was carefully studied.

The above laws of flow could be integrated into a general mathematical formula,

$$Q = K \cdot \pi D^4 / L \qquad \ldots\ldots (9)$$

where K represents a proportionality constant dependent upon the temperature of flow, and the other symbols have the same meaning as

in formula (1). The value of K at a given constant temperature was determined by substitution in the equation,

$$K = QL/PD^4 \qquad \ldots\ldots (10)$$

and for water at 10°C. was found to equal 183.783. Therefore, at 10°C., the flow of water in narrow tubes may be expressed,

$$Q = 183.783 \cdot PD^4/L \qquad \ldots\ldots (11)$$

Poiseuille tested this equation in four tubes of 0.142, 0.065, 0.036, and 0.29 mm. diameter and found that it was correct in each instance.

By solving for K in formula (10) at different temperatures of flow from 0°C. to 45°C., Poiseuille arrived at a general equation for flow at any temperature in this particular range:

$$Q = 1836.724\,(1 + 0.0336793T + 0.0002209362T^2)\,PD^4/L \ . \qquad (12)$$

The actual meaning of the proportionality constant did not become evident until Wiedemann's and Hagenbach's treatment of viscous flow.[4][5] It is now recognized to include the constant $\pi/8$ and the viscosity coefficient, η.

Using Poiseuille's data, Hagenbach calculated the viscosity coefficient of water as equal to 1.3351 centipoises at 10°C. It is currently listed as 1.3097 centipoises.

As an example of the applicability of Poiseuille's general empirical formula (12), we can apply it to data obtained in one of our glass tubes for water flow.

Tube C:

$R = 0.0500$ cm.
$R^4 = 6.24 \times 10^6$
$L = 7.03$ cm.
$P = 20.15$ mm. Hg at 0°C.
$T = 35.0$°C.

By substitution in equation (12), calculated volumetric flow volume equals 80.6 cu.mm./sec. and observed flow volume equals 82.8 cu.mm./sec.

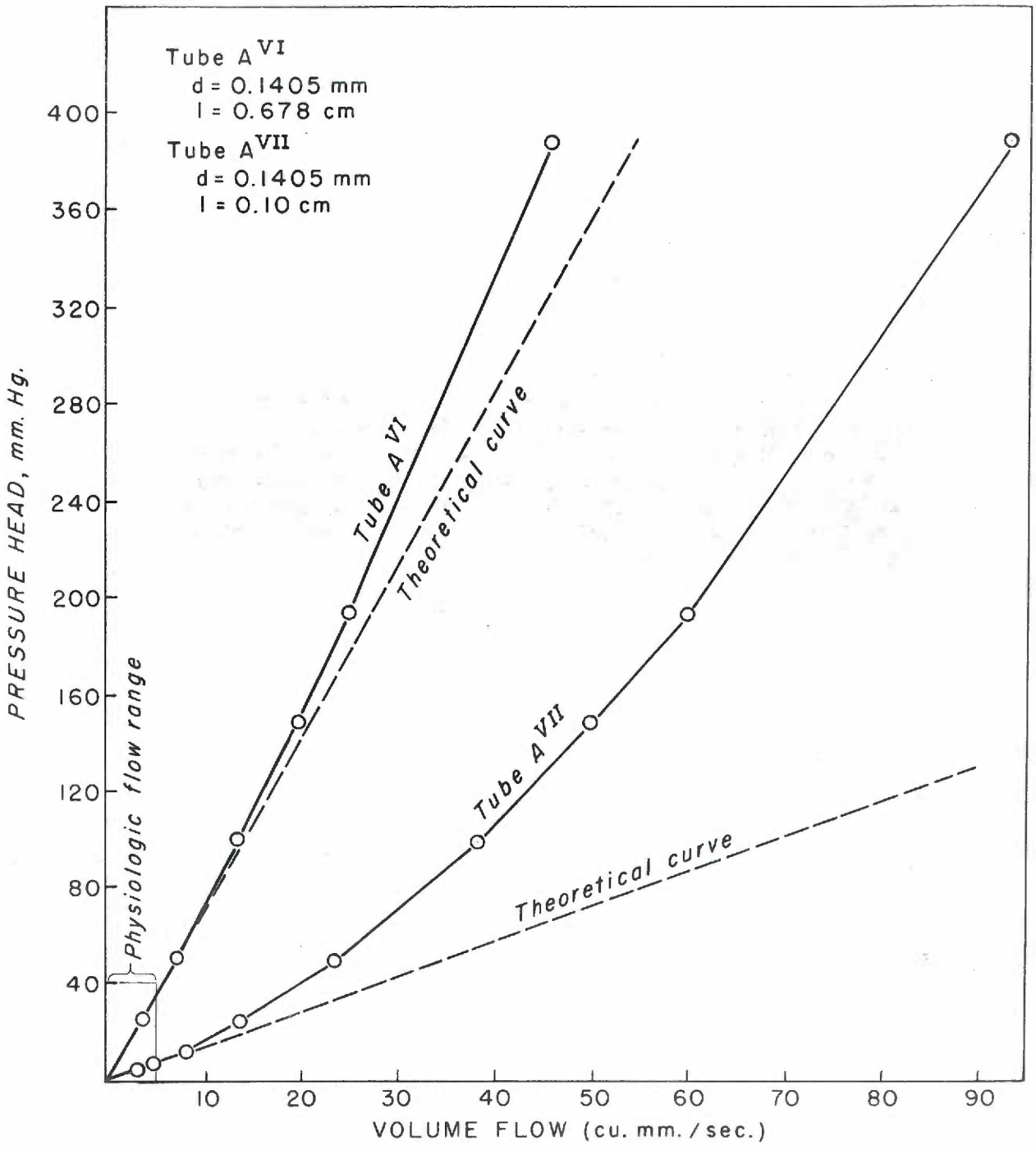
The experimental work of Poiseuille closed the chapter on the laminar flow of water in narrow tubes. The attempt to verify or refute these laws insofar as blood flow in narrow tubes is concerned occupies the remainder of this historical account.

At the beginning of this phase of the discussion, it is necessary to emphasize two aspects of Poiseuille's work which should be borne in mind in applying these laws to blood flow. His law applies only to tubes above a certain critical length, which increases with the radius. Chart 1 is a plot of volumetric rate of flow as a function of pressure in a tube 0.14 mm. in diameter, but whose length is less than this critical minimal value. The data are Poiseuille's and are included in Table 1. Over the wide pressure range which he has employed a significant deviation is observed from the rectilinear relation which would be predicted from Poiseuille's Law. However, in the narrow range in which physiologic velocities of flow occur, no such deviation is observed. Therefore, so long as low velocities are employed, we may assume no significant error due to insufficient tubular length. Secondly, his laws are based on studies in tubes of very narrow diameters. Work conducted in tubes of large diameter may conceivably lead one to an entirely

Chart 1

A plot of pressure-flow data in two tubes which are too short for the application of Poiseuille's Law of Pressures. Note the curvilinear relation between pressure and flow and how this is more marked in the shorter tube. However, in the physiologic flow range indicated by underscoring there is no appreciable deviation from linearity, even in the shortest tube.

CHART I


Tube A VI
d = 0.1405 mm
l = 0.678 cm
Tube A VII
d = 0.1405 mm
l = 0.10 cm
PRESSURE HEAD, mm. Hg.
400
360
320
280
240
200
160
120
80
40
Physiologic flow range
Tube A VI
Theoretical curve
Tube A VII
Theoretical curve
10
20
30
40
50
60
70
80
90
VOLUME FLOW (cu. mm./sec.)

different formula for blood flow in cylindrical tubes, associated primarily with the existence of turbulent flow.

With the exception of the single determination on ox blood, attempted by Poiseuille, the earliest experiments to determine the laws governing blood flow in narrow cylindrical tubes were conducted in 1873 by Duncan and Gamgee.(8) They used a method similar to that devised by Poiseuille, except that their glass tubes were allowed to empty into the atmosphere. Pressure was supplied by a compressed air source. The tubes they employed were relatively large in diameter and are far too short for strict application of Poiseuille's law, particularly since they used high velocities of flow. They were unable to confirm Poiseuille's law even with distilled water, finding that flow varied with the square rather than the fourth power of the diameter. Fresh arterial and venous blood from a calf was forced through these tubes at a mean linear velocity of about 90-100 cm./sec., which is far in excess of a physiologic velocity for vessels of similar diameter. The observed specific viscosities were exceedingly low (2.3) for arterial blood in a tube 0.9289 mm. diameter and 1.3 for fresh venous blood in a tube 1.259 mm. diameter; however, no hematocrits are reported and no mention is made of the pressure or absence of hemolysis. Because of the high flow velocity attained and the large diameter of the tubes, it is felt that these authors are working with an entirely different flow situation than confronted Poiseuille and that their results have limited physiologic significance for peripheral blood flow.

Ewald[9] conducted a more rigorous series of determinations on blood flow in capillary tubes. The value of the constant K in Poiseuille's law was determined by substituting observed values in the equation,

$$K = \frac{Q\,L}{P\,D^4}$$

He called this constant the 'flow coefficient' of the fluid substance. We have already seen that this constant contains the viscosity coefficient according to the relation,

$$K \propto \frac{1}{\eta}$$

and therefore is an expression of the fluidity of a substance, fluidity being the reciprocal of the viscosity coefficient.

By comparing the blood 'flow coefficients' and the water 'flow coefficients' in his data, one may calculate that his observed specific viscosity for human blood ranged from 3.8-5.9. He does not comment upon any error in Poiseuille's law when applied to blood flow.

Lewy[10] in 1897 extended Ewald's work and concluded with him that Poiseuille's law was reasonably accurate for blood flow in horizontal tubes, so long as they were of adequate length and providing that red cell sedimentation was avoided.

Hürthle[11] cannulated the carotid arteries of dogs and placed capillary tubes in direct communication with the vascular bed. Pressure head of flow was varied by partial occlusion of the carotid artery. He also concluded that Poiseuille's law adequately expressed the behavior of blood flow in capillary tubes.

In 1896, Nicolls[12] undertook a theoretical approach to the problem of intravascular viscosity and concluded that blood in the vascular tree could not have a viscosity coefficient greatly in excess of distilled water and still satisfy the known dynamics of the circulation. He began with the equation for the viscosity coefficient derived by Hagenbach,[5]

$$\eta = \pi R^4 \times P/8QL$$

or $\eta = R^2 \times P/8VL$, if one sets $Q = \pi R^2 V$ where V represents the linear velocity in cm./sec.

Since P/L was felt to be exceedingly small in the carotid artery, he concluded that η must also be exceedingly small and assumed that it was not much greater than the viscosity coefficient of water. He then Proceeded to compare water flow and that of defibrinated ox blood in glass capillary tubes and observed specific blood viscosities of 5.6, 5.37, and 5.4 at 33°, 32°, and 16° respectively. Tube dimensions and pressure head of flow were not stated and no comment was made on this apparent deviation from the predicted values.

Numerous limited studies of blood viscosity alterations in disease states began to appear in the German and French literature from 1890. None of them achieved the basic scope we are interested in and no reliable quantitative data were accumulated. Burton-Opitz,[13] using a gravity flow viscosimeter, demonstrated alterations in blood specific viscosity due to certain procedures such as saline infusion, intravenous water injection, and alcohol ingestion. Hirsch,[14]

in 1901, attempted to establish a normal specific viscosity range for humans, but his normal values range from 2 - 9 and are valueless.

Deming and Watson[15] in 1906 made the first extensive application of blood viscosity determinations to clinical medicine; however they contributed to a basic misunderstanding of blood specific viscosity. They used a vertical cylindrical capillary tube (gravity flow) which was popular at that time and were careful to keep temperature constant, having noted that a one degree rise in temperature caused a 2% drop in specific viscosity. The tube they employed for most of their work was 20 cm. long and 0.6 mm. in diameter. They also used a tube 0.3 mm. in diameter and noted that the specific viscosity of a single blood sample was far higher when measured in this tube than it was when determined in the larger tube. This tendency was greatly augmented with blood samples of higher hematocrit. This observation gave impetus to work in German laboratories on the change in specific viscosity of a single blood sample under different pressure heads of flow.

Hess[16] was the first to demonstrate a rise in the specific viscosity of a blood sample as the pressure head of flow was reduced. In 1910 he reported a series of determinations on defibrinated dog's blood. No capillary tube dimensions are given; however, his technique consists of forcing blood and water through a tube under identical pressure heads and measuring the relative volume of efflux. A single sample of dog's blood was found to increase in specific viscosity from

2.67 to 2.89 as the pressure head was decreased from 608 mm. Hg to 90 mm. Hg. If the sample was centrifuged and some plasma withdrawn, the concentrated whole blood increased in specific viscosity from 6.84 to 7.64 as pressure head declined from 650 mm. Hg to 56 mm. Hg.

Rothmann[17] in 1914 reported a series of blood flow determinations in two glass capillary tubes of 0.465 mm. and 0.100 mm. in diameter. The apparatus used was rather cumbersome, although imaginative, and allowed him to measure the acceleration of the meniscus as pressure head was continuously raised in a uniform manner. For a fluid having a constant viscosity coefficient, a constant acceleration of flow should result as the pressure gradient is increased. This was found to be reasonably accurate for a glycerin-water mixture, in the tube 0.465 mm. in diameter. Hirudinized frog's blood behaved in the same manner as the glycerin-water mixture in this larger tube, indicating little change in the viscosity coefficient over a fairly wide range of pressure head (0-100 cm. water). Defibrinated dog's blood, however, showed an 80% decrease in the viscosity coefficient as the pressure head was elevated. This latter observation was true of both hirudinized frog's blood and defibrinated dog's blood when forced to flow through the tube 0.100 mm. in diameter. The percentage drop of specific viscosity was larger in the narrowest tube and with blood of highest hematocrit. Unfortunately, no controls for this narrower tube were given using a glycerin-water mixture. At no time was the flow of pure water tested, nor was the per cent concentration of the glycerin-water mixture stated, so it is impossible to calculate

from these data the exact magnitude of the viscosity coefficients observed. The lengths of the capillary tubes were not included either, so no data on pressure gradient are available from this work. Rothmann concluded that the viscosity coefficient of blood, unlike that of pure fluids, is a variable factor dependent upon the pressure head of flow. It tends to be higher at low pressure heads of flow, and this tendency is exaggerated in bloods of high hematocrit and in tubes of narrower diameter than 0.465 mm. The term "apparent viscosity" or "effective viscosity" is used to describe this phenomenon.

W. Hess[18] supported this conclusion in a publication in 1915 and extended Rothmann's observations using the same technique previously described. No tube dimensions are stated, but the pressure head was varied over a very wide range. Again, it is impossible to determine pressure gradients and linear velocity of flow from the published data. Hess explained the conflict between his and Rothmann's results and those of previous investigators by pointing out that the pressures which were employed in earlier investigations were high enough to give a near-linear relation between pressure and the specific viscosity. Hürthle, for example, used pressures ranging from 99 - 207 mm. Hg, while Ewald used pressure heads in excess of 300 mm. Hg. Hess contends that their data are not inconsistent with his own when this factor is taken into consideration. No physiologic significance was attached to this observation. Its main interest centered about the implications on technique of capillary viscosimetry.

Except for numerous clinical papers and a series of publications concerned with the influence of hematocrit on blood viscosity,[19][20][21] no further work on the flow pattern of blood in narrow tubes was presented until 1931. In that year, Fåhraeus and Lindqvist[1] published an investigation on the alterations of blood viscosity which occur as a function of diameter in very narrow glass tubes. They were aware of the apparent influence of pressure head on blood specific viscosity which Hess[18] and Rothmann[17] had demonstrated and accordingly employed a 100 mm. Hg end to end pressure head; but, because their tubes varied in length, the pressure gradient varied from one tube to another. Since no data on volumetric flow are presented, it is not possible to calculate the mean velocity of flow which these investigators achieved in their capillary tubes; however, a comparison of pressure gradients in their respective tubes and in vessels of similar diameter is listed in Table 2. Data for blood vessels are H. Green's[22] and are approximate. They are based on the assumption of a constant specific viscosity of blood of 4.5, which is about twice the specific viscosity which Fåhraeus and Lindqvist report in their smallest tubes. Therefore, even if the pressure gradients were equal in the two instances, the linear velocity of flow in Fåhraeus' tubes would be almost double that calculated for blood vessels. Actually, the pressure gradients employed in Fåhraeus' work were two to three times that reported by Green, and this suggests that Fåhraeus was working with blood flowing at a mean velocity considerably in excess of physiologic for vessels of similar diameter.

They reported a progressive decrease in the specific viscosity of a single blood sample as it passed through progressively narrower tubes. In extending their interpretation to conditions in the vascular bed, they state that "the resistance to the flow of blood in the arterioles (and in the small veins) is considerably less than would be the case if the streaming of the blood followed the law of Poiseuille . . .". This conclusion overlooks the fact that linear velocity in the arterioles is exceedingly slow, which on the basis of the German workers' researches would suggest just the opposite effect.

According to Fåhraeus and Lindqvist[1][23] the physical basis for their result is to be found in the suspension stability of blood. They believe that in tubes under 0.3 mm. in diameter red cells tend to aggregate in the axial stream of flow, thereby creating a relatively cell-free plasma zone peripherally. This behavior is felt to reduce the effective viscosity coefficient of whole blood towards that of plasma. Evidence was also presented that the hematocrit in small capillary tubes is decreased when blood is forced through them. This was determined by aspirating blood through capillary tubes and determining the hematocrit of the blood sample contained within the tube upon cessation of flow.

Müller[24] has recently reported a decrease in the viscosity coefficient of a blood sample as tubular diameter is progressively decreased from 2.0 cm. to 0.076 mm. However, in each capillary tube, the viscosity coefficient is observed to rise as linear velocity is decreased. This tendency is exaggerated below average linear

velocities of 5 cm./sec. regardless of tube diameter. The viscosity coefficients which are charted are extraordinarily high, and even in the smallest tube the magnitude of the specific viscosity varies from 3.8 - 4.3 at 15°C.

The prevailing opinion regarding blood flow in narrow tubes may be summarized by stating that the specific viscosity of blood is considered to be an inconstant value dependent upon both the linear velocity of flow and the diameter of the tube through which flow is occurring. Because of this, the classic equation of viscous laminar flow, Poiseuille's Law, is not considered to be applicable to blood flow in narrow capillary tubes or in the small vessels of the cardiovascular system.

METHODS

All previous work on blood flow in glass tubes has been done using viscosimeters which will maintain either a constant pressure head of flow or a consistently changing pressure head and measuring the volume of blood which flows in a unit of time. This is then compared with water flow at the same pressure head, and the specific viscosity of blood is calculated according to formula 7 (Page 7).

This constant pressure technique has been adopted for part of this investigation; however the bulk of the work reported here is based on another approach. Blood or water is forced through a capillary tube at a known volumetric rate of flow and the pressure head generating this flow is measured continuously. The specific viscosity may then be calculated according to formula 8 (Page 9). The reason for using this procedure is that different blood samples may be compared at identical linear velocities of flow, which is not possible if one uses a constant pressure viscosimeter. Changes in specific viscosity due to changes in linear velocity of flow are eliminated by this method, and the influence of hematocrit may be more accurately evaluated. Also, any tendency for clot formation is minimized in this apparatus. Instead of resulting in progressively slower flow and enhancement of clot formation, as occurs in a constant pressure apparatus, any clot formation tends to cause a rapid increase in pressure head and a "blowing-out" of the impediment.

Regardless of the method used in collecting the data, they are presented in the form of a pressure-flow plot for each sample tested.

In each tube, a series of such plots has been determined and the specific viscosity data may be derived from these graphs rather than from isolated determinations.

Constant Flow Technique:

The apparatus is arranged as diagramed in Figure 1. Volumetric rate of flow is controlled by means of a constant rate injector machine to which is attached any of three calibrated syringes. By interchanging these syringes it is possible to cover a flow range from 0.3-200 cu.mm./sec.

Volumetric Flow. The injector machine (Model D-1150.0, Martin Hubbard) uses a Graham variable speed transmission which drives a threaded piston at a constant number of r.p.m. The exact linear velocity of this piston is controlled by varying the contact points of three tapered rollers to a conical drive shaft, contact at the narrow end resulting in low velocity. A dial on the machine housing has 40 velocity settings, each of which delivers a constant volumetric rate of flow from a given syringe.

Because of the friction transmission principle, the instrument was calibrated against a wide range of pressure head. The extremes of 4-200 mm. Hg produced no change in linear velocity of the screw-threaded piston. The volumetric output of each syringe was tested over the entire range of dial settings, these calibration data appearing in Table 3 and plotted in Chart 2.

Capillary tubes. The capillary tubes employed in this study are of three types. Hypodermic needle tubing ranging in diameter

Figure 1

Constant flow apparatus. The syringe (d) is clamped to the injector machine and the screw-threaded piston (e) is brought in apposition to the syringe plunger. Linear velocity of the screw thread is regulated by the velocity dial (a) and (b). Pressure is recorded via stopcock (g) and a lead or glass tubing (h) as flow commences through the capillary tube (i). The capillary tube discharges below the surface of saline in the reservoir (j). The standing pressure head at the tube's exit must be subtracted from the observed pressure head at (g).

Samples are stored in capped hypodermic syringes in the water bath and are introduced into the calibrated syringe via the stopcock (e). Rapid changing of blood samples is therefore possible.

Fig. 1

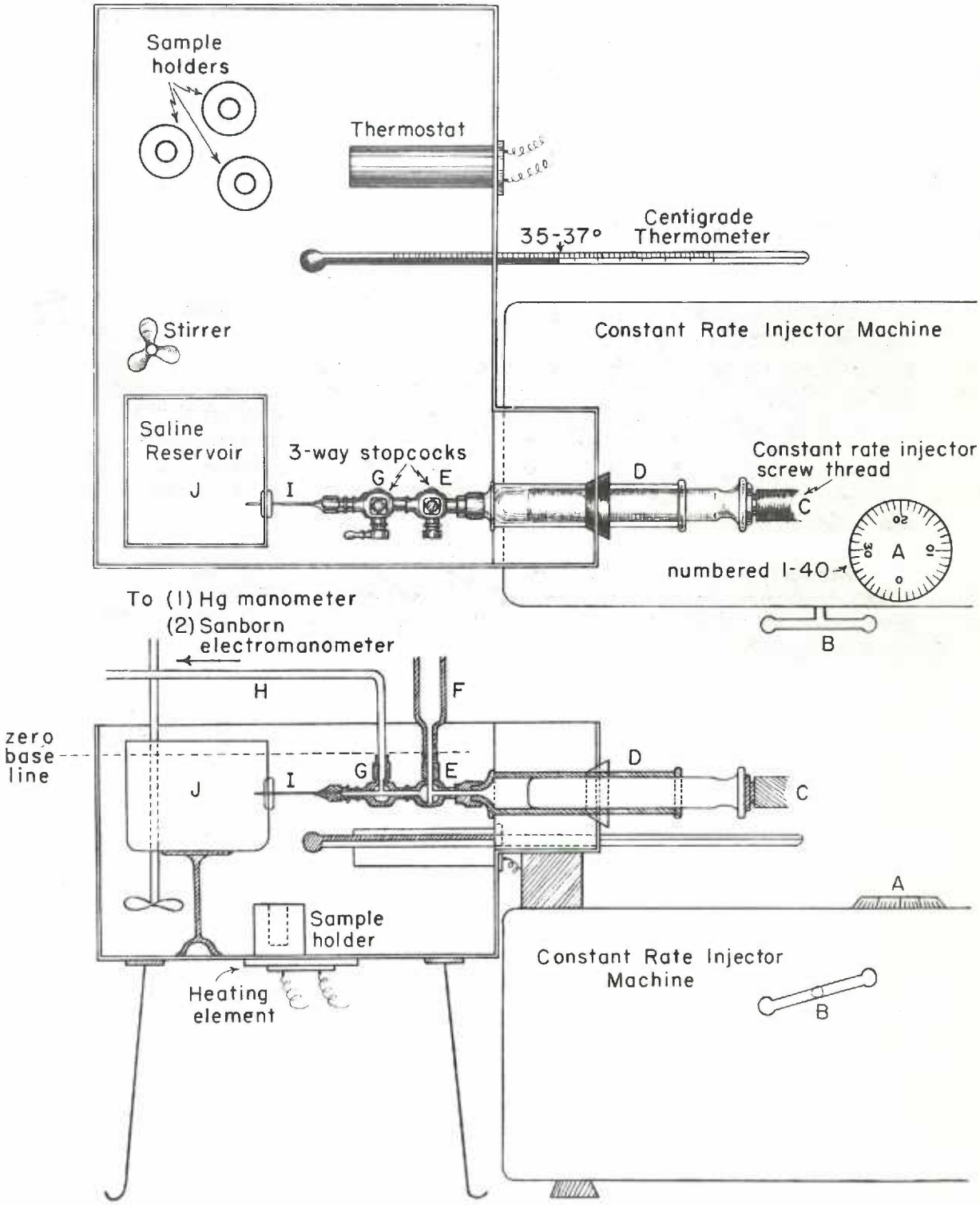

Sample holders
Thermostat
35-37°
Centigrade Thermometer
Stirrer
Constant Rate Injector Machine
Saline Reservoir
J
3-way stopcocks
G
E
I
D
Constant rate injector screw thread
C
numbered 1-40
A
B
To (1) Hg manometer
(2) Sanborn electromanometer
H
F
zero base line
J
I
G
E
D
C
A
Sample holder
Heating element
Constant Rate Injector Machine
B

Chart 2

(a) Plot of dial setting-volume rate of flow for each syringe over the entire velocity dial range. The inset is regraphed in 2b.

(b) Large scale plot of the inset in 2a. Most of the work reported utilizes this flow range.

CHART 2a

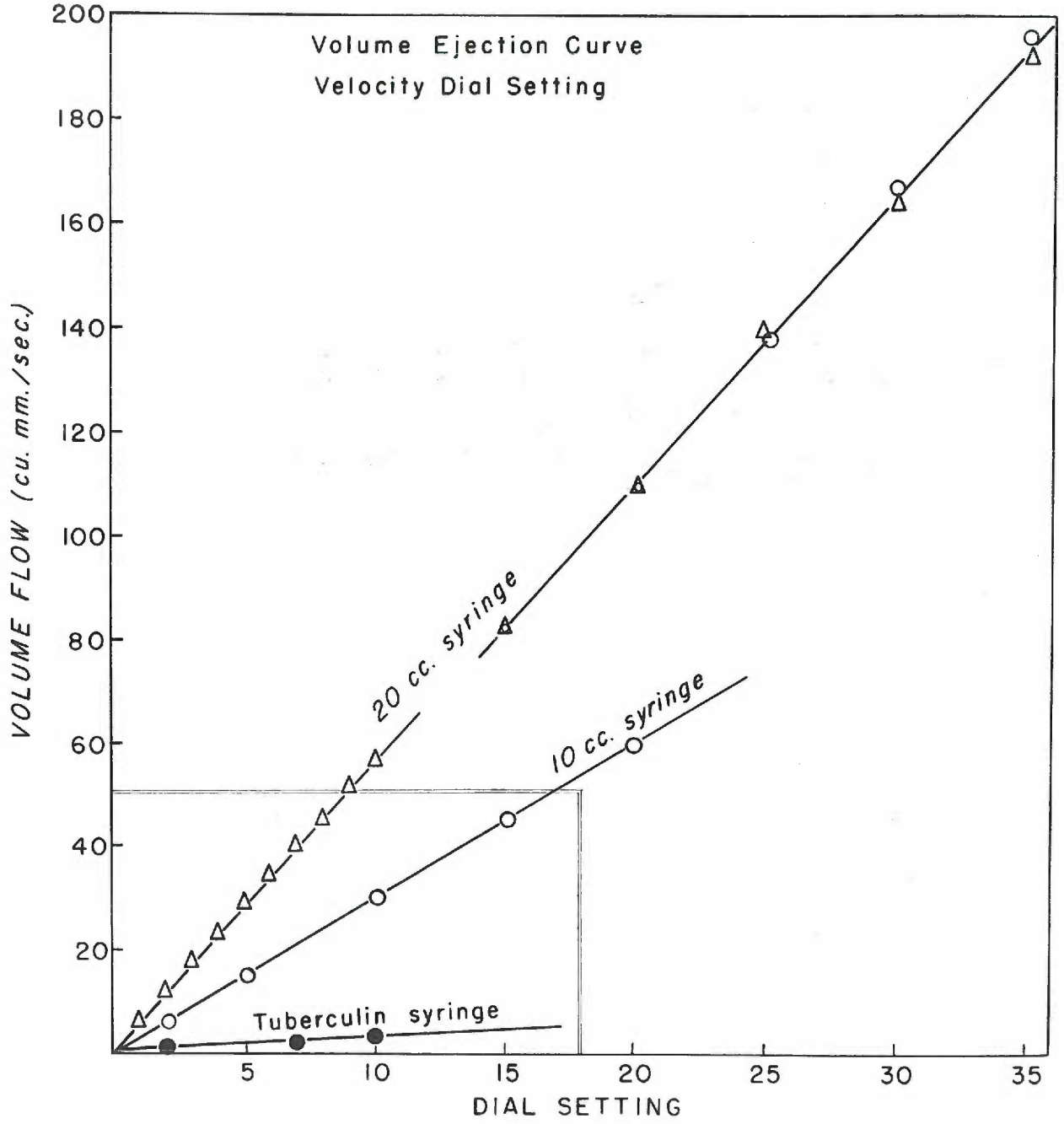
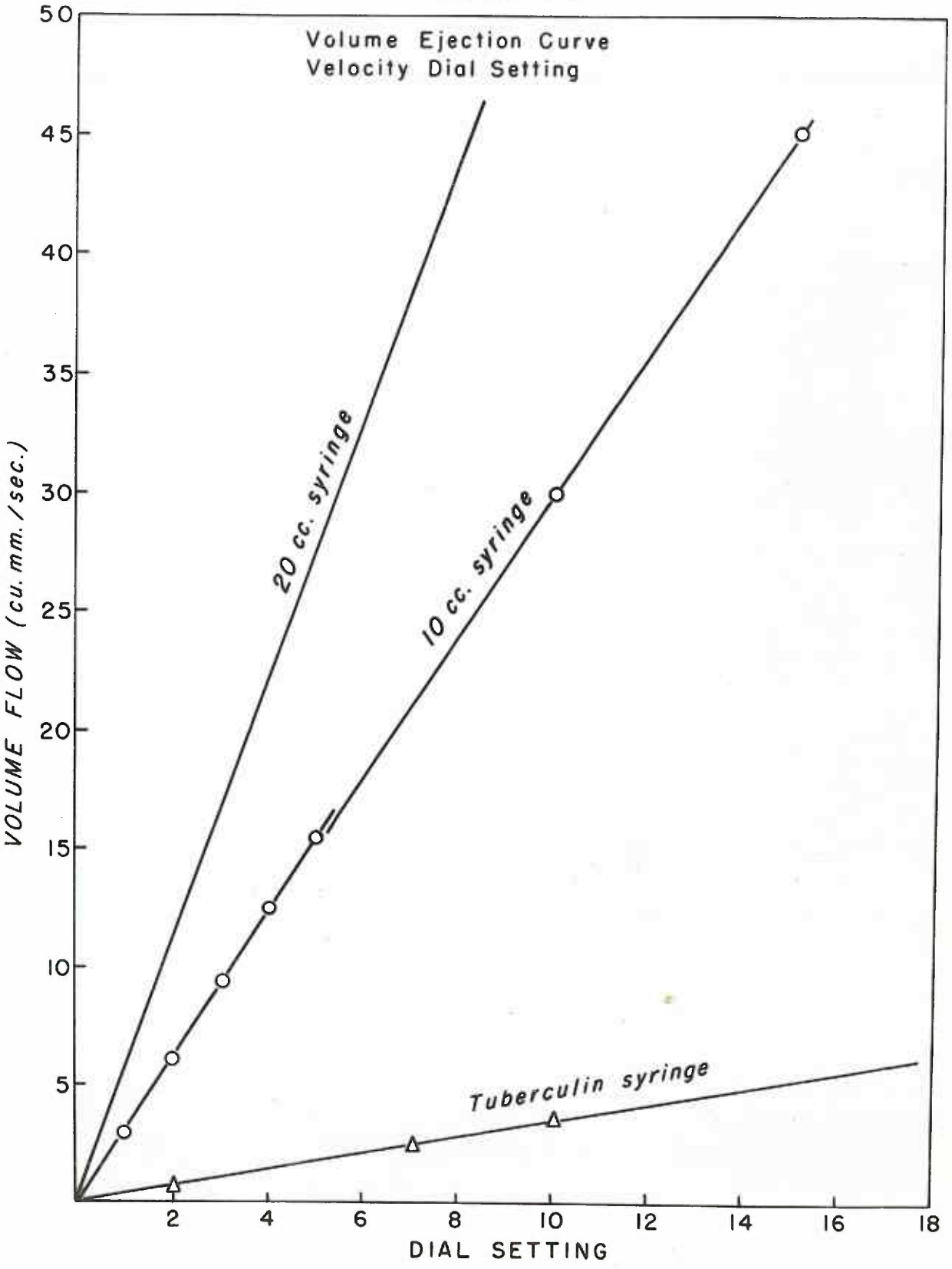

Volume Ejection Curve
Velocity Dial Setting
VOLUME FLOW (cu. mm./sec.)
200
180
160
140
120
100
80
60
40
20
20 cc. syringe
10 cc. syringe
Tuberculin syringe
5
10
15
20
25
30
35
DIAL SETTING

CHART 2 b


Volume Ejection Curve
Velocity Dial Setting
VOLUME FLOW (cu. mm./sec.)
50
45
40
35
30
25
20
15
10
5
20 cc. syringe
10 cc. syringe
Tuberculin syringe
2
4
6
8
10
12
14
16
18
DIAL SETTING

from 0.20 mm. to 0.58 mm. has proven to be satisfactory although the exact diameter is difficult to establish (tube dimensions are listed in Table 4). For this reason only glass capillaries whose bores can be observed and measured have been utilized for more quantitative work.

Specially made silicon borate precision bore tubes were supplied by Fisher and Porter Company. They were cast in molds about a wire of known diameter, and this wire was withdrawn after cooling had occurred. Each tube was approximately seven centimeters in length, and a small cone was ground in each end to avoid turbulence at the entrance and exit of the capillary bore. The measured length of the capillary bore excludes this conical region. The diameter of each tube was determined by filling the lumen with a translucent contrast medium, immersing the entire tube in cedar oil (refractive index 1.51) and measuring the width of the colored column with an ocular micrometer. A stylus of known external diameter was inserted into the lumen of several tubes and its diameter measured with the ocular micrometer as a check on the accuracy of the technique. The diameters of these tubes are measurable within three microns by this technique and are listed in Table 4. Uniformity of bore and cross-sectional area also were checked by this method and no detectable variation in either factor could be demonstrated.

Because neither the hypodermic tubing nor the precision bore glass tubing extend down to the diameter range used by Fahraeus, a technique was devised using ordinary soft glass tubing heated and drawn out to any desired diameter. The dimensions of these tubes were measured

under the ocular micrometer in the same manner as were the precision bore tubes. Since the bores were not uniform, they were measured every 2 millimeters along their entire length.

All tubes were fixed in rigid communication with the syringe-reservoir by means of a Luer-Lok adapter and were arranged to discharge under the surface of saline kept in a separate container that was immersed in the constant temperature bath. This eliminated any surface tension effect at the efflux end of the capillary tube.

Temperature. The entire flow system including most of the syringe was immersed in a constant temperature water bath. Temperature was kept within a ±0.5° temperature range for each experiment and within a range of 35° to 37° for the research as a whole. A maximum error of 2% may occur in each experiment with this degree of temperature control.

Pressure Head. The lateral pressure head of flow was determined by recording from the side arm of a three-way stopcock arranged as a T-tube and interposed into the flow system just proximal to the capillary tube. A mercury manometer was used in the first five experiments. However, excessive volume displacement into the manometer system tended to dilute the blood in transit through the capillary and also necessitated an excessive time for pressure stabilization. A Sanborn electromanometer proved more effective in eliminating both of these objections, although requiring more careful attention in setting up an exact zero reference base line.

It is necessary to know the effective pressure head with great accuracy. Failure to do this may easily lead one to an erroneous impression of blood viscosity changes for reasons which will be explained. Corrections must be made for position of the manometer zero, capillarity of the manometer and the standing head of saline at the efflux end of the capillary tube. The saline reservoir was sufficiently large in cross-sectional area so as to result in an increase of saline head of only 2-3 mm. water during each experiment. It was possible to automatically correct for this saline head when using the Sanborn manometer by raising or lowering the transducer element until it was at the level of the saline in the reservoir. This level was maintained throughout the experiment as the zero reference plane. (See Fig. 1)

Pressure records were run continuously while flow was being maintained. There was a zero reference line at the beginning and end of each series of runs and pressure standards were made against a mercury or water manometer at the end of each flow determination. The maximum error observed in standardizing the manometer in this manner was 10% although errors of 1-3% were the rule. Table 5 lists the results of calibration of the Sanborn manometer induced by progressive increments of pressure from the machine's own mercury manometer. The most likely source for the discrepancy between the mercury manometer and the Sanborn is the error in reading the mercury manometer. Comparison of several pressures recorded by the Sanborn is undoubtedly more accurate.

The maximum pressure heads which could be recorded by the Sanborn were approximately 450 mm. Hg as illustrated in Chart 3.

All pressures were calculated as pressure gradients and expressed as mm. Hg per cm. length of tube. This is the only logical way to handle this variable.

Flow Samples. Distilled water has been used almost without exception for the control liquid. This must be kept dust-free for work in the smaller tubes. In tubes greater than 0.4 mm. diameter, this contamination has no obvious effect and ordinary tap water may be used as a standard. A 40% or 45% glycerol-water mixture has also been used as a control fluid. Samples of the pressure-flow curves which are obtainable with water are illustrated in Chart 4. Each plot is representative of a separate tube.

Blood for this investigation came from two sources. Most of the work in the larger tubes (0.6 mm. - 0.4 mm. diameter) required a fairly large volume of blood for each series of determinations. For this diameter range Red Cross blood which was free from visible hemolysis was found to be satisfactory. This blood was treated in an identical manner with fresh blood.

Fresh venous blood, drawn without stasis into a heparinized syringe, was used for all the work in the narrower diameter range. No other anticoagulant was used than the heparin coating the syringe. The heparin contained 1,000 Provisional International units per cc. Blood was stored by capping the syringe and immersing this in the constant temperature bath, so that the blood sample was below the surface of the bath.

Chart 3

Demonstration of maximum pressure limit of the Sanborn electromanometer. Pressure-flow curves are for water, 25% glycerol, 70% glycerol, and blood of hematocrit 43. The tube used was III. It is evident from this that 450-500 mm. Hg is the maximum attainable pressure head which can be tolerated by the transducer element.

CHART 3

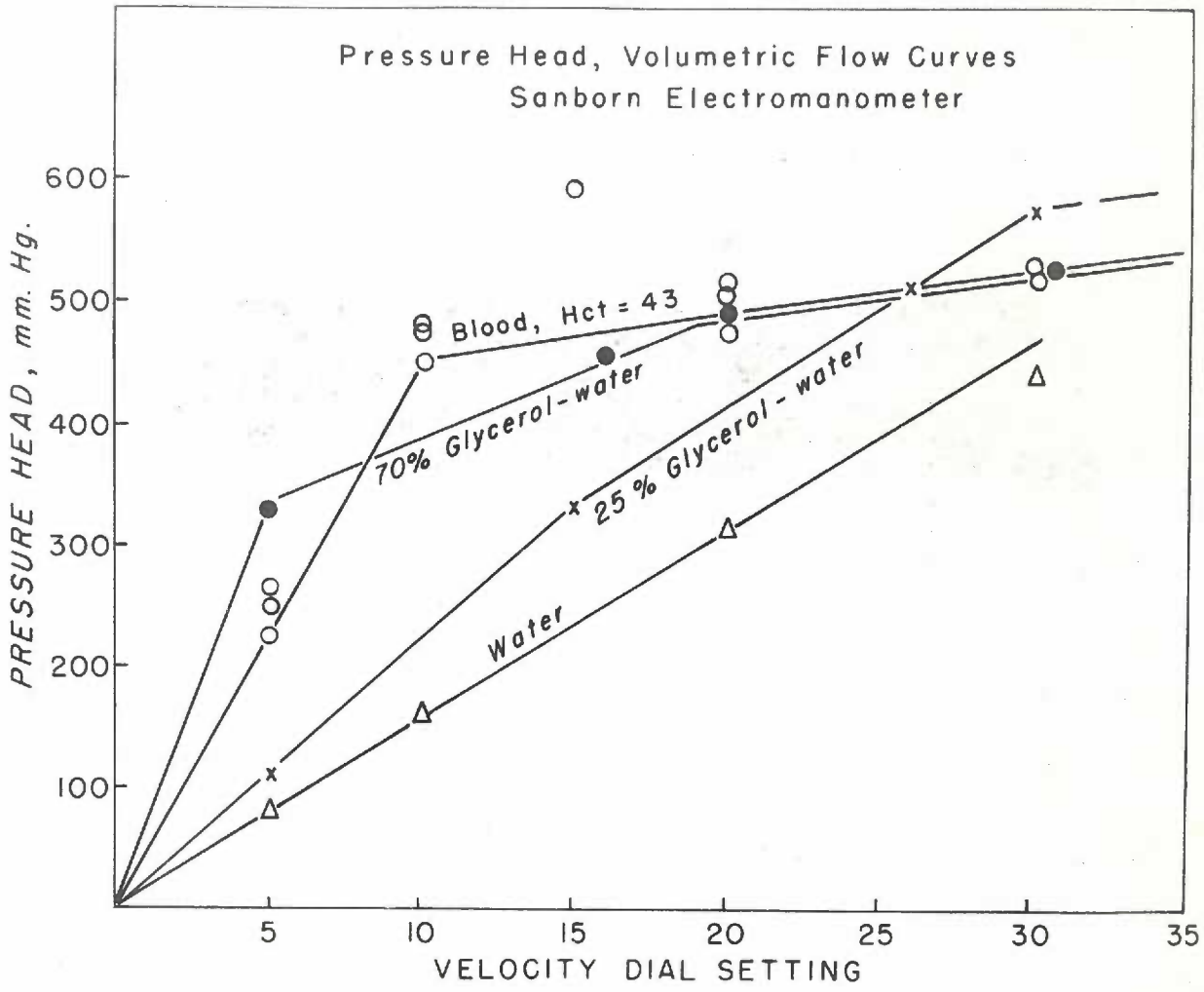
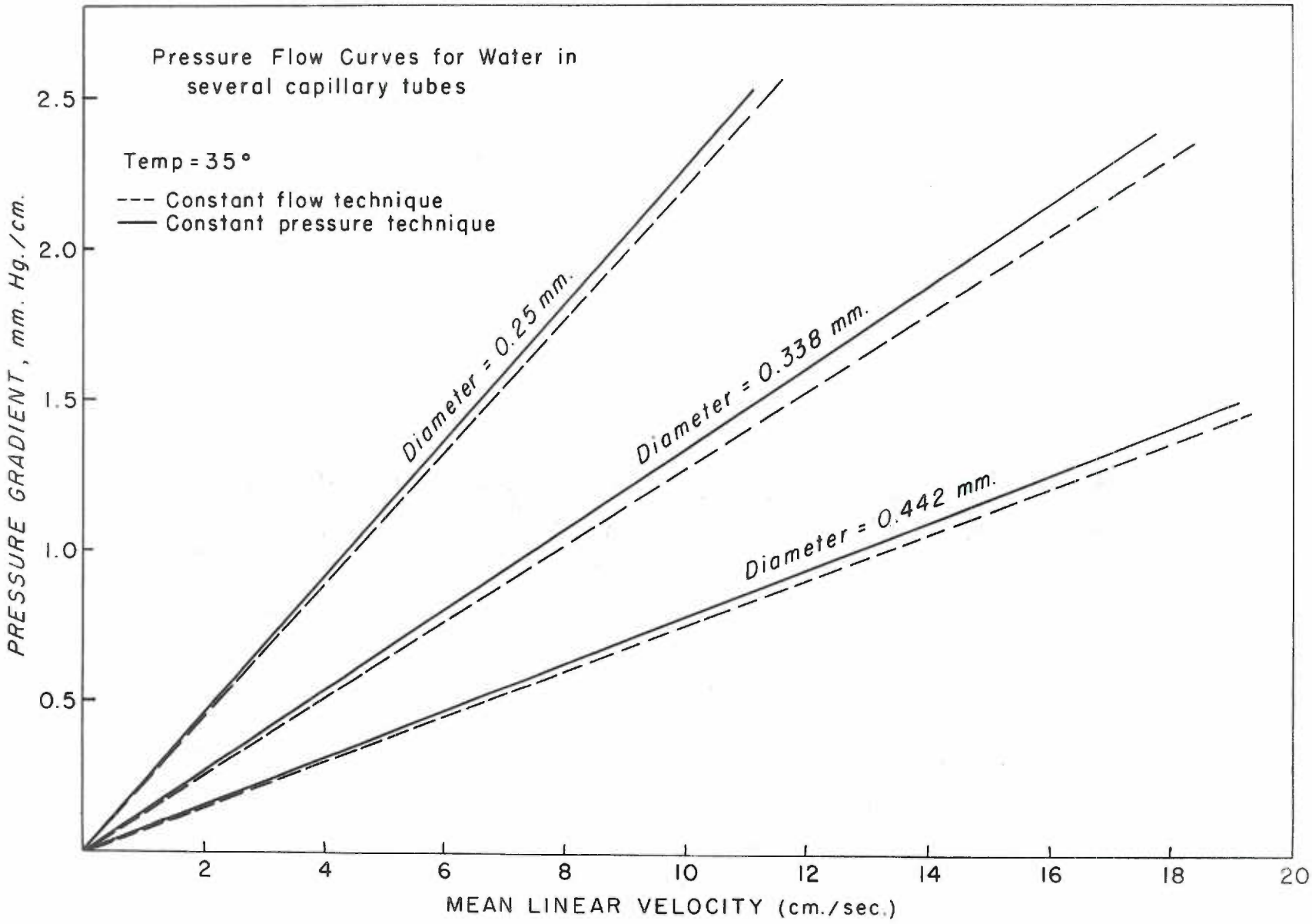

Pressure Head, Volumetric Flow Curves
Sanborn Electromanometer
PRESSURE HEAD, mm. Hg.
600
500
400
300
200
100
5
10
15
20
25
30
35
VELOCITY DIAL SETTING
Blood, Hct = 43
70% Glycerol-water
25% Glycerol-water
Water

Chart 4

A plot of water flow as a function of pressure gradient in each of several capillary tubes. Each line is labeled with the diameter of the tube through which flow is occurring. Broken lines are constant pressure data; solid lines are constant flow data.

CHART 4


Pressure Flow Curves for Water in several capillary tubes
Temp = 35°
--- Constant flow technique
— Constant pressure technique
Diameter = 0.25 mm.
Diameter = 0.338 mm.
Diameter = 0.442 mm.
PRESSURE GRADIENT, mm. Hg./cm.
2.5
2.0
1.5
1.0
0.5
2
4
6
8
10
12
14
16
18
20
MEAN LINEAR VELOCITY (cm./sec.)

Hematocrits were done in duplicate in a centrifuge developing 1,600 G. and were spun down to constant volume. Duplicates checked within ±0.5 units in all cases.

Procedure. The entire flow system from syringe to capillary tube was flushed with saline three times. The capillary tube was filled with the heparin solution and allowed to stand for 20 minutes to an hour. Blood was then introduced into the calibrated syringe and discharged via the capillary tube. Two to five cc's. were used to flush the system in this manner before any determination was attempted.

Arbitrary volumetric flow rates (dial settings) were chosen for each tube in order to embrace a physiologic velocity of flow. Pressure head was recorded throughout each determination. Runs usually were done in duplicate, but checks were so close in most instances that one reading would suffice.

Thus, a given blood sample was forced through a capillary tube at each of four or more volumetric rates of flow, the pressure head across the tube being recorded in each instance. The pressure gradient was then calculated, as was the average linear velocity of flow. A plot was constructed of linear velocity of blood flow as a function of pressure gradient. A similar plot was made for water, and a comparison between the two at any velocity of flow in the observed range was greatly facilitated. These plots, which were set up to test Poiseuille's Law of Pressures, form the basic data for this phase of the investigation.

Constant Pressure Technique:

Volume Flow. Two calibrated blood reservoirs were used in this method. A 5 cc. graduated pipette was used for blood flow in the diameter range 0.58 mm. - 0.40 mm. Below this diameter, volumetric rate of flow was so slow that an appreciable error due to red cell sedimentation occurred. Therefore, a 0.20 cc. graduated pipette was employed for this range. The pipettes were arranged as diagramed in Figure 2 and the meniscus timed between the two end calibrations with a manually operated stopwatch.

Tubing. The capillary tubing employed in this technique was the same as that used in the constant flow procedure. However, more observations were made in the precision bore capillary tubes by this method. The tubes were fastened to the calibrated reservoir by a rubber connection and an interposed T-tube whose internal diameter was in excess of 1 mm. This T-tube facilitated the filling of the flow system, but did not appreciably impede flow because of its relatively large diameter.

Temperature. Temperature was controlled as before. All flows were corrected to 35°C. by use of Poiseuille's empirical temperature correction factor, $(1+0.0337T + 0.000221T^2)$, where T is the temperature in degrees centigrade.

Pressure Head. Pressure head of flow was established by pumping air into the reservoir from a hand bulb until a desired pressure was attained. Progressive release of air then allowed one to measure flow at successively lower pressure heads. At the conclusion, the pressure was again raised in the system and a check run was made to rule out

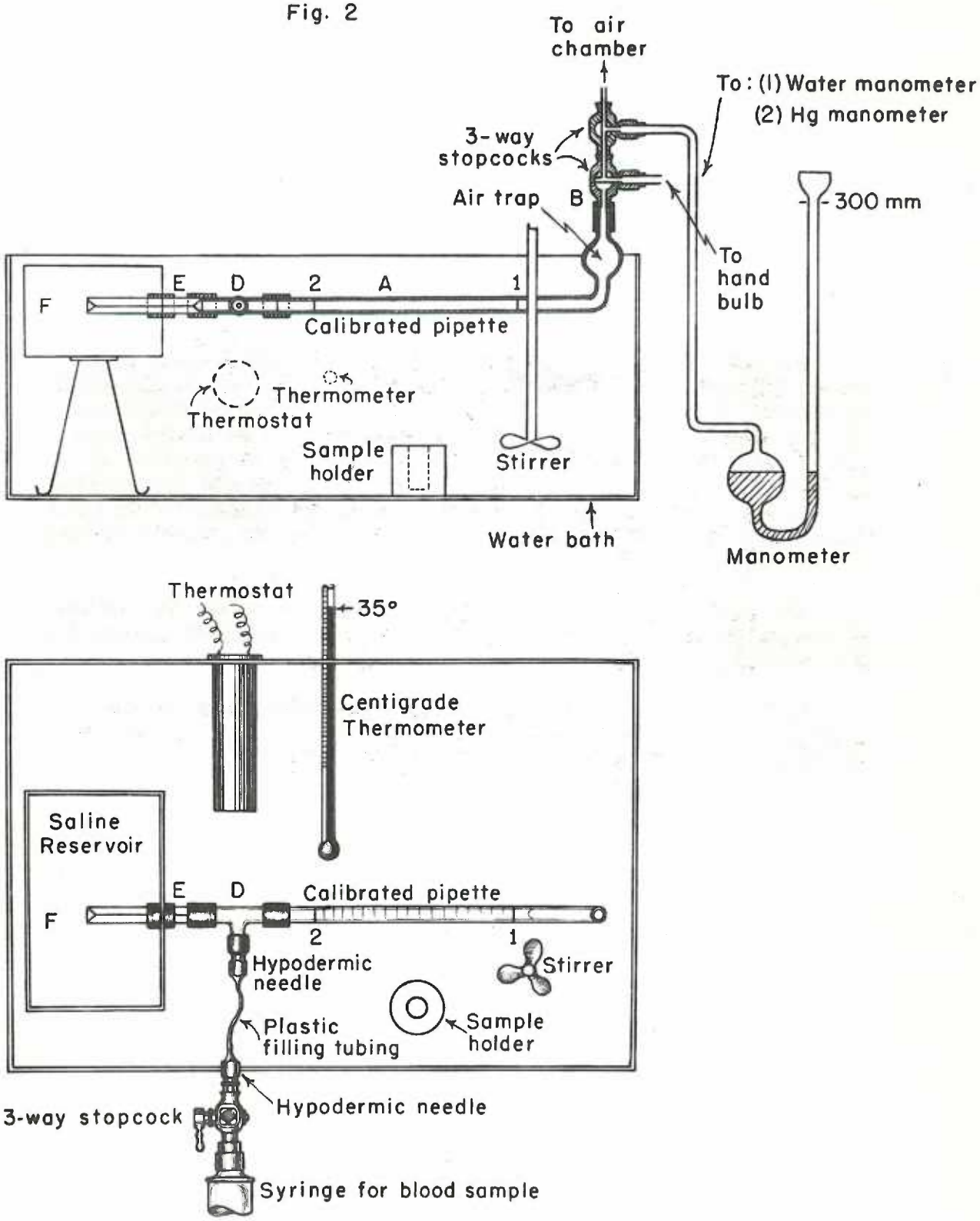
Figure 2

Diagram of constant pressure apparatus. A calibrated horizontal pipette (a) is immersed in the water bath. It is connected at one end to a 20 liter glass air chamber by means of stopcocks (b) and (c). These are arranged to permit air to be forced into the chamber from a hand bulb and the pressure to be recorded by either a mercury or water manometer. At the other end the pipette is connected to a capillary tube (e) via an interposed T-tube (d). This facilitates the introduction of fluid into the pipette without interfering with flow.

The capillary tube is arranged to discharge below the surface of saline contained in the reservoir (f), and a pressure correction must be made for this standing head of saline.

Blood is stored in capped, heparinised syringes which are immersed in the water bath. It is introduced into the pipette via the stopcock, plastic filling tube, and the T-tube (d).

Fig. 2


To air chamber
To : (1) Water manometer
(2) Hg manometer
3-way stopcocks
Air trap
B
300 mm
To hand bulb
F
E
D
2
A
1
Calibrated pipette
Thermometer
Thermostat
Sample holder
Stirrer
Water bath
Manometer
Thermostat
35°
Centigrade Thermometer
Saline Reservoir
F
E
D
Calibrated pipette
2
1
Hypodermic needle
Stirrer
Plastic filling tubing
Sample holder
3-way stopcock
Hypodermic needle
Syringe for blood sample

clot formation in the capillary tube. Either a water manometer or a mercury manometer was used. Pressure head at no time varied more than ±1.5 mm. of water during a single determination. The pressure was recorded at the beginning and end of each run, and the average was used for further calculations. Corrections for the capillarity of the manometer as well as the 200 cu. mm. pipette were necessary to calculate accurate pressure gradients.

Flow Samples. Water and blood were collected and stored as described for the constant flow technique. Hematocrits were also done in identical fashion.

Procedure. Pressure was built up in the air chamber by forcing in air with a hand bulb via stopcocks (b) and (c). Stopcock (c) was then turned to shut off the air chamber-manometer system from the rest of the apparatus.

The pipette reservoir (a) and capillary tube (e) were filled with the heparin solution and allowed to remain filled for 20 minutes to one hour. This solution was then forced out of the flow system by briefly opening stopcocks (b) and (c) to the air chamber. Stopcock (c) was again closed and stopcock (b) turned to communicate with the atmosphere via the hand bulb. The pipette was now filled with blood. At the beginning of each experiment or in changing from one sample to another, several wash-outs were made through the capillary tube.

As the blood meniscus passed scratch mark #1 on the pipette during filling, stopcock (b) was turned to communicate with stopcock (c) thus creating an air pocket between the surface of the blood and stopcock (c).

An additional volume of blood was now forced into the pipette and stopcock (h) was closed. Flow commenced immediately through the capillary tube due to the compression of air in the aforementioned air pocket. Thus, no stagnation of blood in the capillary tube was allowed. Stopcock (c) was now turned as diagramed in Figure 2, and flow continued under a constant pressure head. The meniscus was timed from mark #1 to mark #2, pressure and temperature were recorded, the pressure was reduced via the air bulb and another run was started.

RESULTS

The results are presented under three main headings: The Law of Pressures, The Law of Diameters, and The Law of Hematocrit. In the section dealing with the law of pressures two techniques were used which will be known as the Constant Pressure Technique and the Constant Flow Technique. The experiments in this section will be subdivided according to the technique by which the data were obtained.

The Law of Pressures.

Regardless of the technique employed to gather data, the same basic information eventually is obtained; namely, temperature of flow, tubular dimensions, volumetric rate of flow and the pressure head. From these data a plot may be constructed of average linear velocity of flow as a function of the pressure gradient. All the data in this section are presented in such graphic form accompanying the discussion of the experiment. Tables of data are included in the appendix.

Constant Flow Technique.

Experiment No. 1: Chart 5; Table 6

This experiment is presented as an illustration of a serious pitfall in the measurement of blood specific viscosity and may serve to explain some of the discrepancy between the results reported here and those of previous studies.

According to Poiseuille's Law of Pressures, the velocity of a viscous fluid should be a rectilinear function of the pressure gradient, so long as laminar flow exists; and the plot of these functions should intersect both axes at zero. Failure to observe this relation in a tube of proper dimensions could only mean (1) that the fluid is not obeying the laws of laminar flow or (2) that there is an error in technique.

In Experiment No. 1, (Chart 5a), the flow curve for water is seen to be a perfectly straight line. However, it does not intercept the pressure axis at zero, but at minus one mm. Hg. Similarly, each of the blood flow curves in Experiment No. 1 are seen to be perfectly straight lines with a common intercept on the pressure axis of minus one mm. Hg. Since the pressure gradient ranges up to 38 mm. Hg/cm. in this experiment, such an error may not seem significant. As a matter of fact, if one had failed to plot these flow curves and had calculated the specific viscosity of blood by comparing pressure gradients of blood and water at each of several velocities of flow, one would gain an erroneous impression. Blood specific viscosity, so calculated, would rise to infinity at a linear velocity of 8 cm./sec. This is illustrated in the lower right gradient of Chart 5a.

The water flow plot is the control. The viscosity coefficient of water does not change at low linear velocities of flow, so that failure of the water flow line to intersect the axis at zero implies errors in technique. The net effect of such errors in this instance is an observed pressure gradient that is 1 mm. Hg lower than the actual pressure gradient. Thus, an error -3.5 mm. Hg has occurred in reading the pressure head of flow. Since the water flow plot is linear this identical error has occurred with each reading. The same applies to the blood flow curves. It is necessary to correct empirically the recorded pressure head of water flow by +3.5 mm. Hg in each instance, and so doing shifts the line upwards in parallel fashion so that it intercepts the axis at zero. The blood flow data must be treated in the same manner, since the technique was identical with that for water flow.

The result of correcting the pressure heads, based on the water flow control plot, is to cause the three lines to intercept at zero. There is, therefore, no change in the ratio of blood pressure gradient/water pressure gradient over all observed velocities of flow. The specific viscosity of the blood samples is constant under the experimental conditions.

An empirical correction of pressure head of flow, based on the known behavior of water flow, is less desirable than accurate technique and instrumentation; nevertheless, it is legitimate and necessary in order to obtain a true concept of blood viscosity behavior.

Experiment No. 2: Chart 5(b); Table 6

The conditions of this experiment are identical with those in Experiment No. 1. The blood samples are from a freshly expired Red Cross donor's bottle in which no visible hemolysis had occurred. Plasma withdrawn from this bottle was used as a diluent for the concentrated blood sample which remained. This permitted one to make up samples having a wide hematocrit range. To avoid unnecessary complexity, only three of the six blood samples are plotted. The others are also linear and have a zero intercept on the pressure axis.

Experiment No. 3: Chart 5(c); Table 6

The observations in the previous experiments were not anticipated on the basis of existing reports in the literature. As a final check on their validity a mixture of approximately 45% glycerol and water was made up as a control liquid.

Several blood samples were prepared as before and tested in the same tube as the glycerol-water mixture. As may be seen in chart 5(c), there is no qualitative difference between the pressure-flow plot of such a control and the blood samples, each of them being linear with a zero intercept.

Chart 5

(a) Pressure-flow plots of water and two blood samples in a tubing 0.51 mm. in diameter. Flow was at room temperature and the velocity extended over a 20 cm./sec. to 100 cm./sec. range. A mercury manometer was employed.

(b) Pressure-flow plots of water, plasma, and three blood samples in a tube 0.51 mm. in diameter. Flow was at room temperature and the velocity range is the same as in (a). A mercury manometer recorded pressure.

(c) Pressure-flow plots of water, plasma, 40% glycerol, and three blood samples in a tube 0.51 mm. in diameter. Flow conditions were identical to those in charts (a) and (b).

CHART 5a

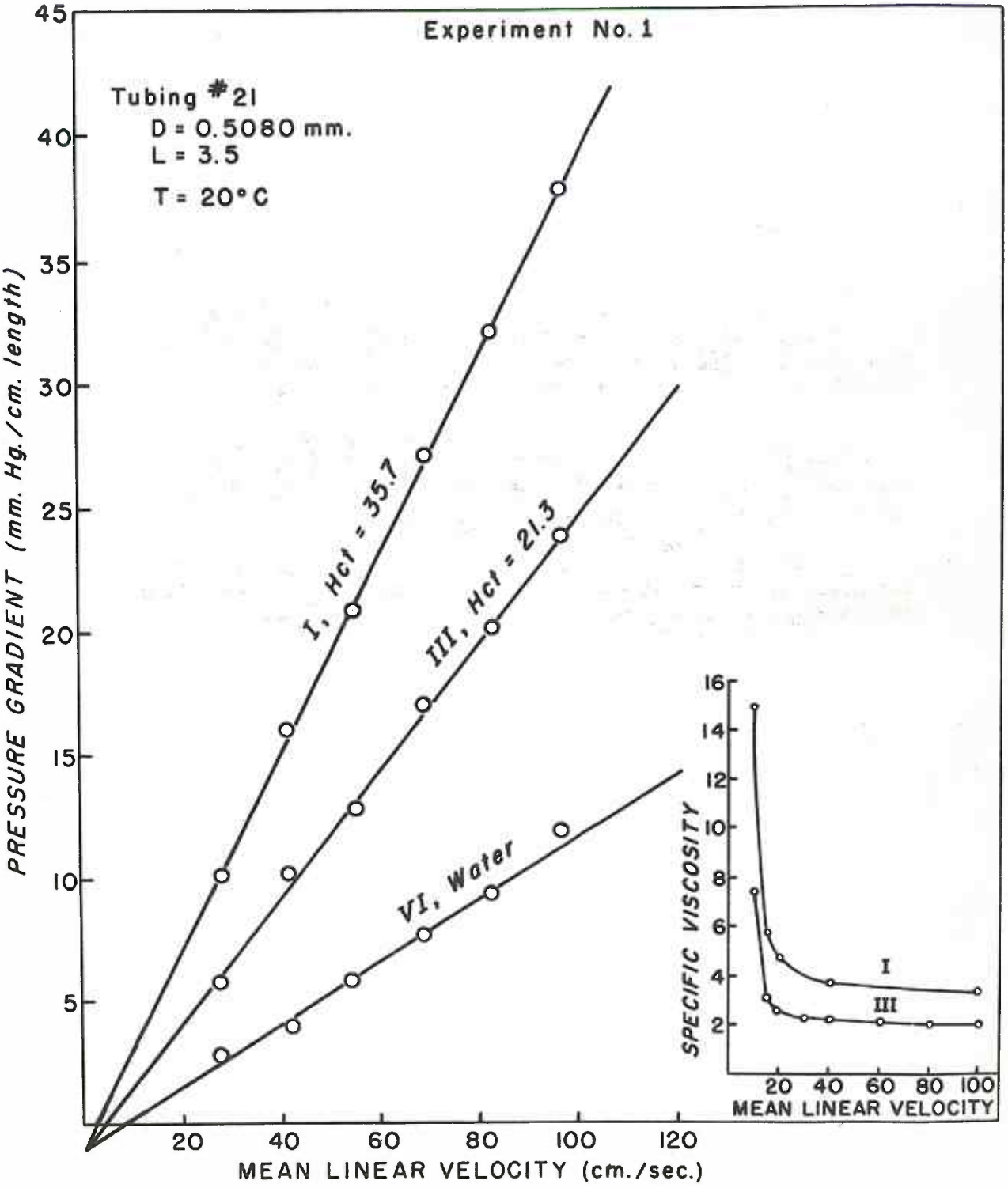

Experiment No. 1
Tubing #21
D = 0.5080 mm.
L = 3.5
T = 20° C
I, Hcl = 35.7
III, Hcl = 21.3
VI, Water
PRESSURE GRADIENT (mm. Hg./cm. length)
MEAN LINEAR VELOCITY (cm./sec.)
SPECIFIC VISCOSITY
I
III
MEAN LINEAR VELOCITY

CHART 5 b

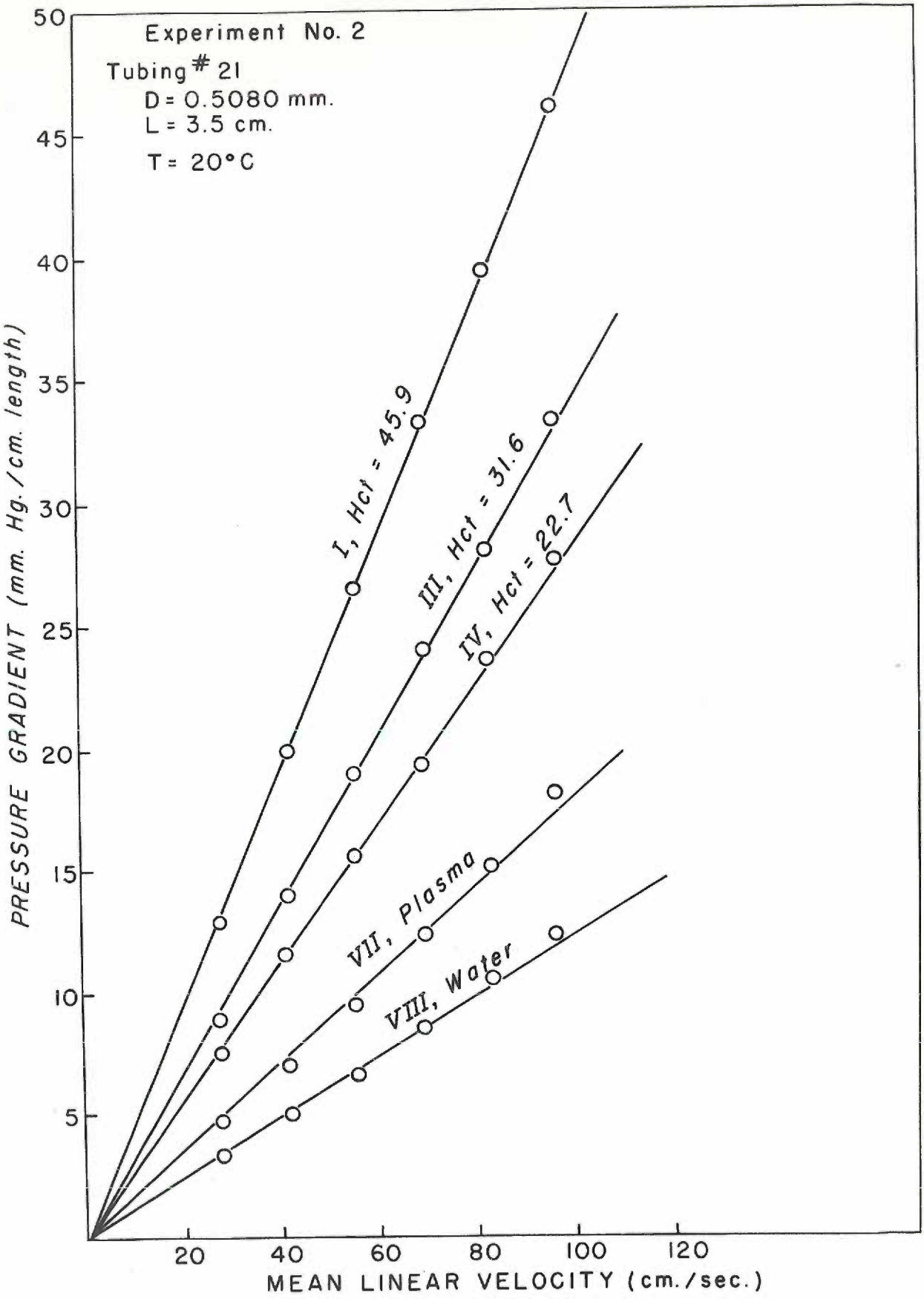
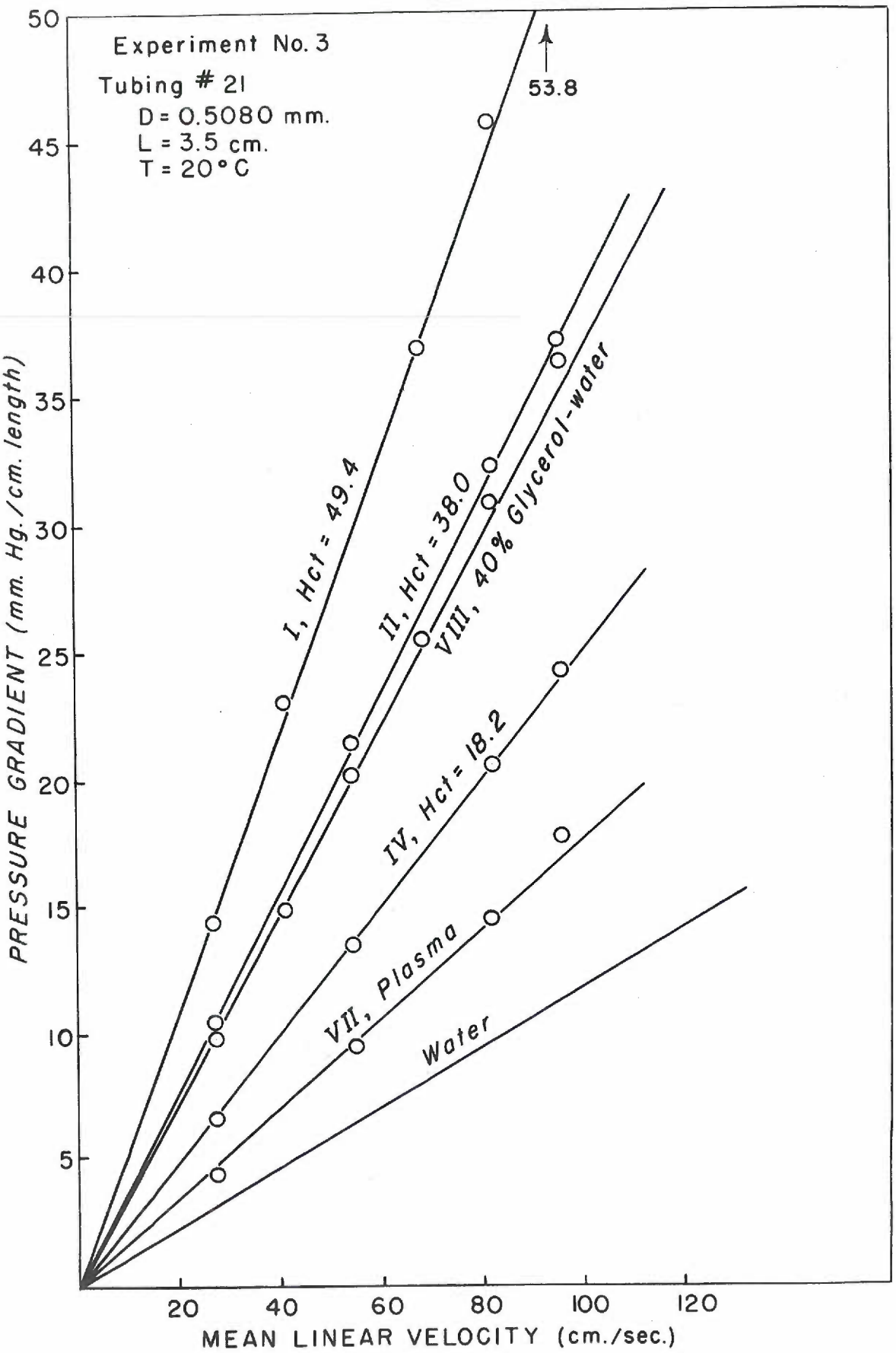

Experiment No. 2
Tubing # 21
D = 0.5080 mm.
L = 3.5 cm.
T = 20°C
I, Hct = 45.9
III, Hct = 31.6
IV, Hct = 22.7
VII, Plasma
VIII, Water
PRESSURE GRADIENT (mm. Hg./cm. length)
MEAN LINEAR VELOCITY (cm./sec.)
5
10
15
20
25
30
35
40
45
50
20
40
60
80
100
120

CHART 5 c


Experiment No. 3
Tubing # 21
D = 0.5080 mm.
L = 3.5 cm.
T = 20° C
53.8
I, Hct = 49.4
II, Hct = 38.0
VIII, 40% Glycerol-water
IV, Hct = 18.2
VII, Plasma
Water
PRESSURE GRADIENT (mm. Hg./cm. length)
MEAN LINEAR VELOCITY (cm./sec.)
50
45
40
35
30
25
20
15
10
5
20
40
60
80
100
120

Experiment No. 4: Chart 6(a); Table 7

The previous experiments were conducted at room temperature in tubing 0.5 mm. in diameter and at high linear velocities of flow. This experiment is designed to extend the observations to a lower velocity in a narrower tube and employ a physiologic temperature.

A #25 hypodermic needle was selected and pressure was recorded with the mercury manometer. By using a 10 cc. syringe, velocities as low as 11 cm./sec. were observed in this tube.

The blood was sampled as before. Two blood samples, a plasma sample and a water control are presented in chart 6(a).

Experiment No. 5: Chart 6(b); Table 7

The conditions in the previous experiment are duplicated in this. The results for three blood samples and a plasma sample are seen to be identical with those in Experiment No. 4. At the highest velocities of flow, the mercury manometer was not allowed sufficient time to equilibrate. Considerable trouble was also encountered because of the excessive displacement of blood into the manometer system resulting in both wastage and hemodilution. Because of this, the mercury manometer was abandoned and a Sanborn electromanometer substituted for all further work with the constant rate injector machine.

The underscored velocities in Chart 6(b) indicate the approximate physiologic velocity in a blood vessel of similar diameter.

Chart 6

(a) Pressure-flow plots of water, plasma, and two blood samples in a tube 0.25 mm. in diameter. Flow temperature was 37°C. and the velocity was varied from 10 cm./sec. to 110 cm./sec.

(b) Pressure-flow plots of water, plasma, and three blood samples in a tube 0.25 mm. in diameter. Flow conditions were identical with those in (a), however insufficient time was allowed for manometer stabilization at the highest velocities of flow.

CHART 6a

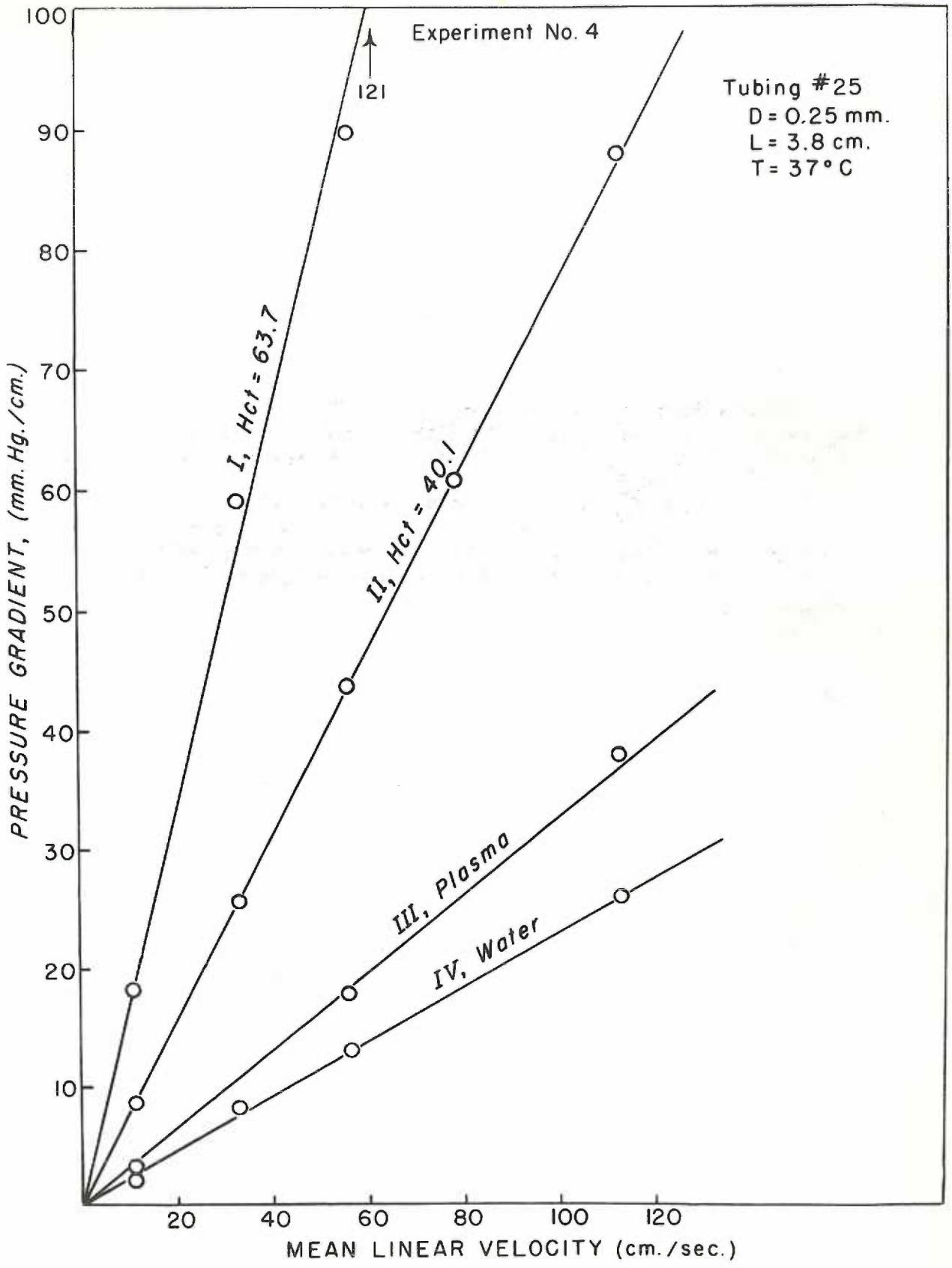
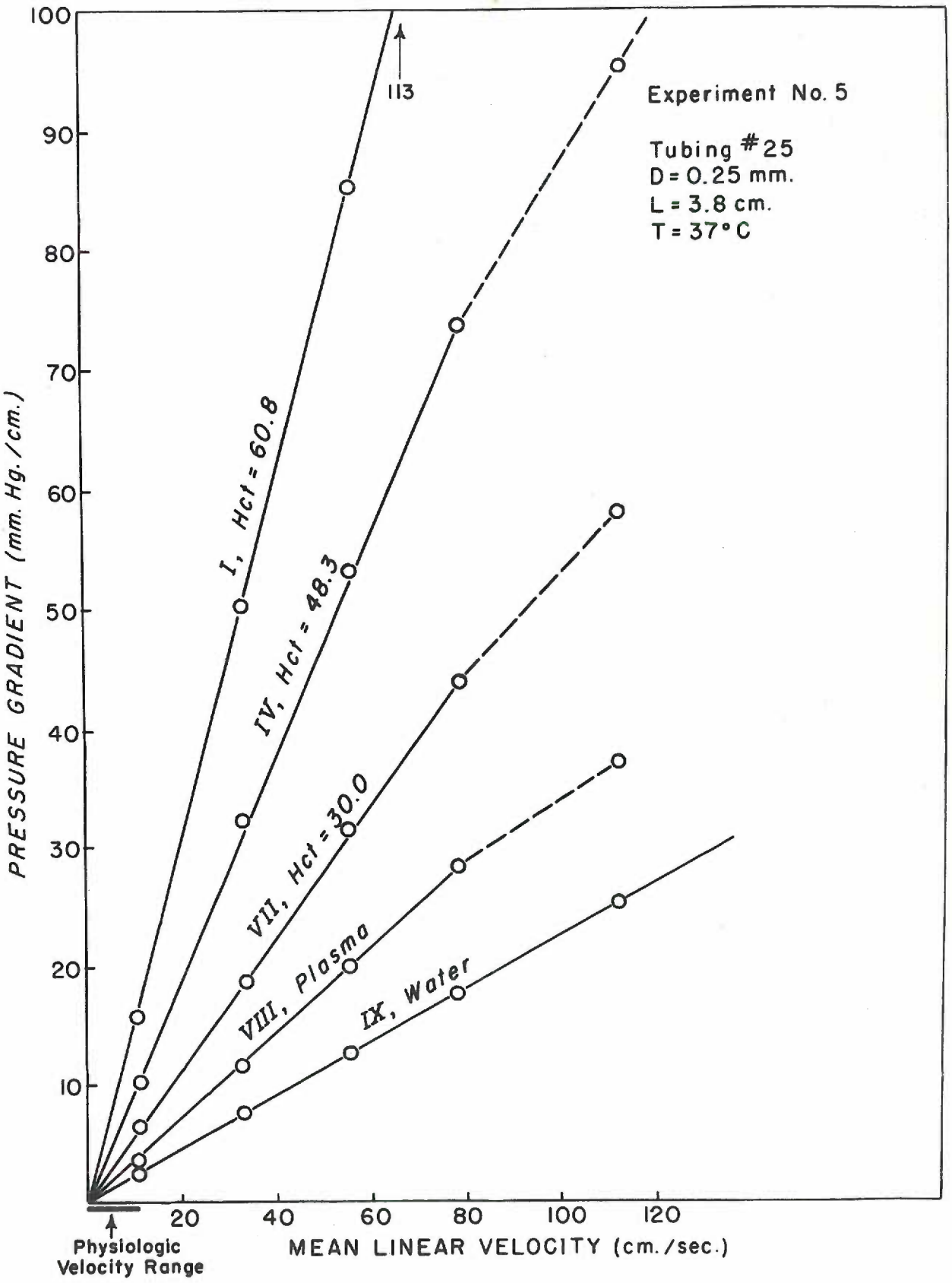

Experiment No. 4
121
Tubing #25
D = 0.25 mm.
L = 3.8 cm.
T = 37° C
I, Hct = 63.7
II, Hct = 40.1
III, Plasma
IV, Water
PRESSURE GRADIENT, (mm. Hg./cm.)
MEAN LINEAR VELOCITY (cm./sec.)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120

CHART 6b


Experiment No. 5
Tubing #25
D = 0.25 mm.
L = 3.8 cm.
T = 37° C
113
I, Hct = 60.8
IV, Hct = 48.3
VII, Hct = 30.0
VIII, Plasma
IX, Water
PRESSURE GRADIENT (mm. Hg./cm.)
MEAN LINEAR VELOCITY (cm./sec.)
Physiologic Velocity Range
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120

Experiment No. 6: Chart 7, Table 8

In this experiment a tuberculin syringe was used as a blood reservoir, and pressure was recorded by the Sanborn electromanometer. The same tube was employed as in Experiments No's. 4 and 5.

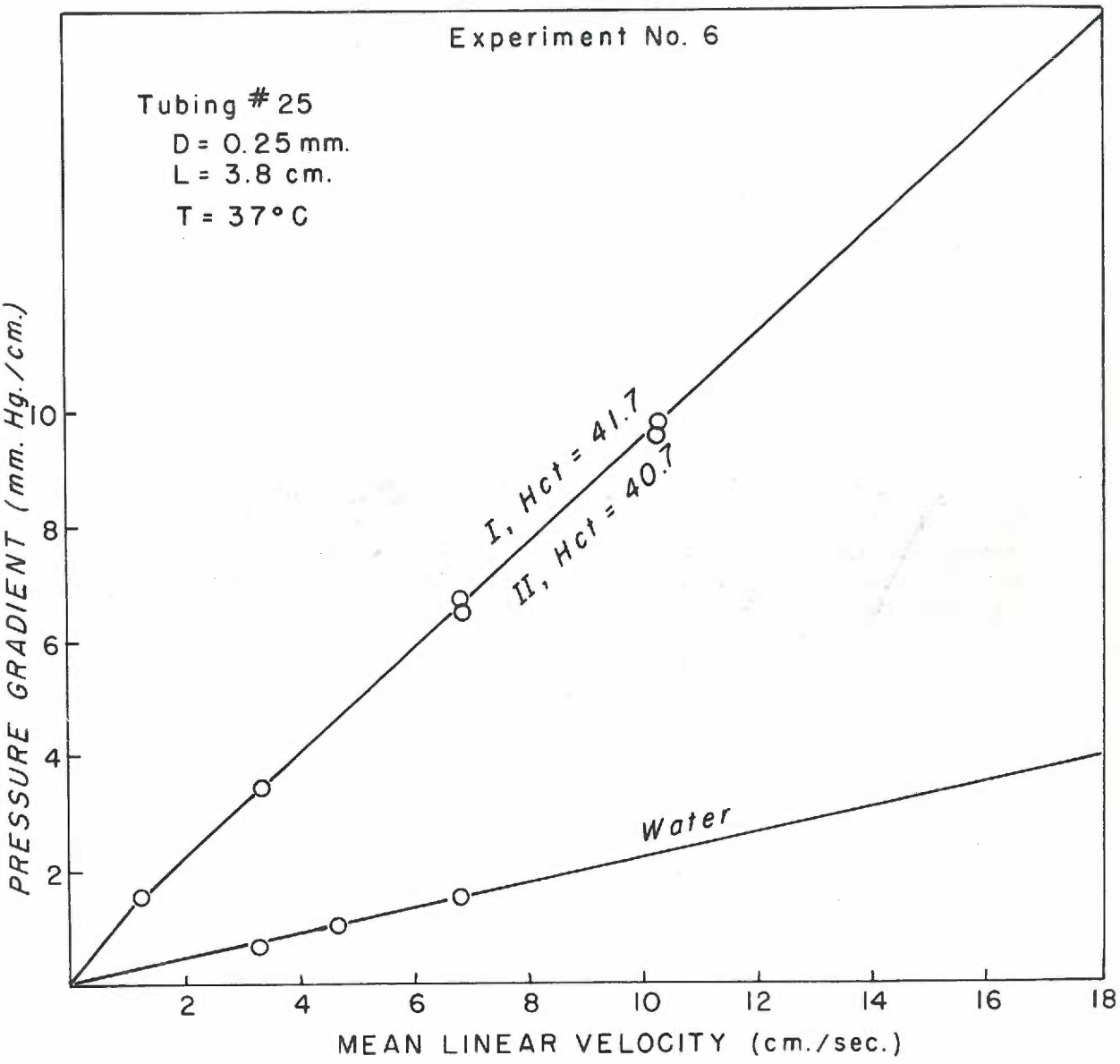
Duplicate fresh blood samples of Hct. 40.7 and 41.7 were used and the linear velocity of flow was varied over a range from 10.3 cm./sec. - 1.2 cm./sec. This embraces the physiologic range for a vessel 0.25 mm. diameter.

In this experiment the blood flow plot, if extrapolated as a straight line, would intercept the pressure axis at +0.36 mm. Hg. This implies that a pressure of 0.36 mm. Hg/cm. tube would need to be applied before flow would commence. In a tube whose diameter is 30 - 40 times that of a red cell, this seems improbable; therefore, the plot is extrapolated to zero.

Chart 7

Pressure-flow plot of water and two blood samples in a tube 0.25 mm. in diameter. A tuberculin syringe was used to reduce velocity of flow to a range of 1 cm./sec. to 10 cm./sec. The temperature of flow was 37°C. Pressure was recorded by a Sanborn electromanometer.

CHART 7


Experiment No. 6
Tubing # 25
D = 0.25 mm.
L = 3.8 cm.
T = 37° C
I, Hct = 41.7
II, Hct = 40.7
Water
PRESSURE GRADIENT (mm. Hg./cm.)
MEAN LINEAR VELOCITY (cm./sec.)
2
4
6
8
10
12
14
16
18

Experiment No. 7: Chart 8; Table 9

This was undertaken later in the same day as Experiment No. 6, using the same blood samples but employing a hypodermic tubing #27 (0.20 mm. in diameter). Although the run with Sample I was in error, it demonstrated an exceedingly interesting point. The entire determination of Sample I was completed and the pressure gradients calculated when it was noted that they were unusually high for a tube of this diameter. The behavior was not as it is in clot formation when there is a rapid, but transient, increase in pressure head. In this case the partial occlusion was permanent. The apparatus was disassembled and the tube inspected under the microscope. At the distal end, a solid piece of material was observed wedged in the lumen. It was removed after much manipulation of the stylus, and the remainder of the experiment was conducted with a patent tube. The effect of this partial occlusion on the blood flow curve of Sample I is obvious in Chart 8. Normally the flow curves for I and II would be superimposed, as they are in Experiment No. 6, Chart 7. Marked as the effect was on the slope of the curve, no deviation from linearity is observed over a velocity range that may be presumed to be physiologic for a vessel of this diameter. In addition the intercept was at zero, as it was for II and the water control.

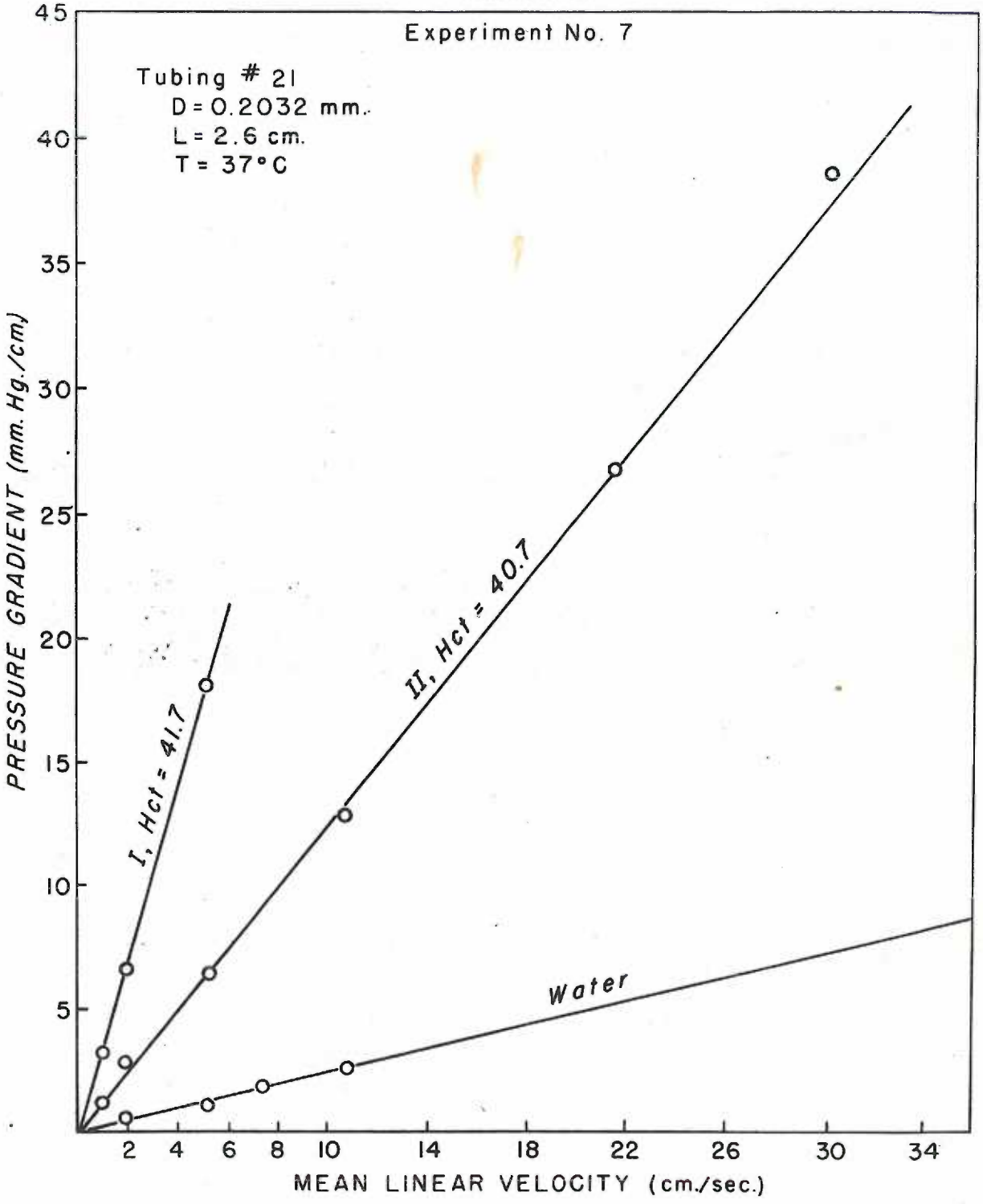
Of additional interest in this experiment is the observation that the specific viscosity of blood sample II is 5.1, which is on the high side rather than the low for blood of this hematocrit. Yet this tube is sufficiently narrow to be able to demonstrate the so-called 'Fahraeus effect' a decrease in specific viscosity.

Chart 8

Pressure-flow graphs of water and two blood samples in a tube 0.20 mm. in diameter. The graph for blood sample #1 was obtained in the presence of a partial occlusion of the lumen. The exact diameter, and hence the exact average velocity of flow, cannot be stated for this flow sample. Regardless of this, the relation is seen to be linear with a zero intercept.

Blood sample #2, of the same hematocrit as #1, was studied in the patent tubing. The water control was also obtained in the patent tube. Flow velocity for these latter two determinations varied from 1 cm./sec. to 30 cm./sec. Temperature was kept at 37°C. and pressure was recorded with the Sanborn manometer.

CHART 8


Experiment No. 7
Tubing # 21
D = 0.2032 mm.
L = 2.6 cm.
T = 37°C
I, Hct = 41.7
II, Hct = 40.7
Water
PRESSURE GRADIENT (mm. Hg./cm)
MEAN LINEAR VELOCITY (cm./sec.)
45
40
35
30
25
20
15
10
5
2
4
6
8
10
14
18
22
26
30
34

Experiment No. 8: Chart 9; Table 10

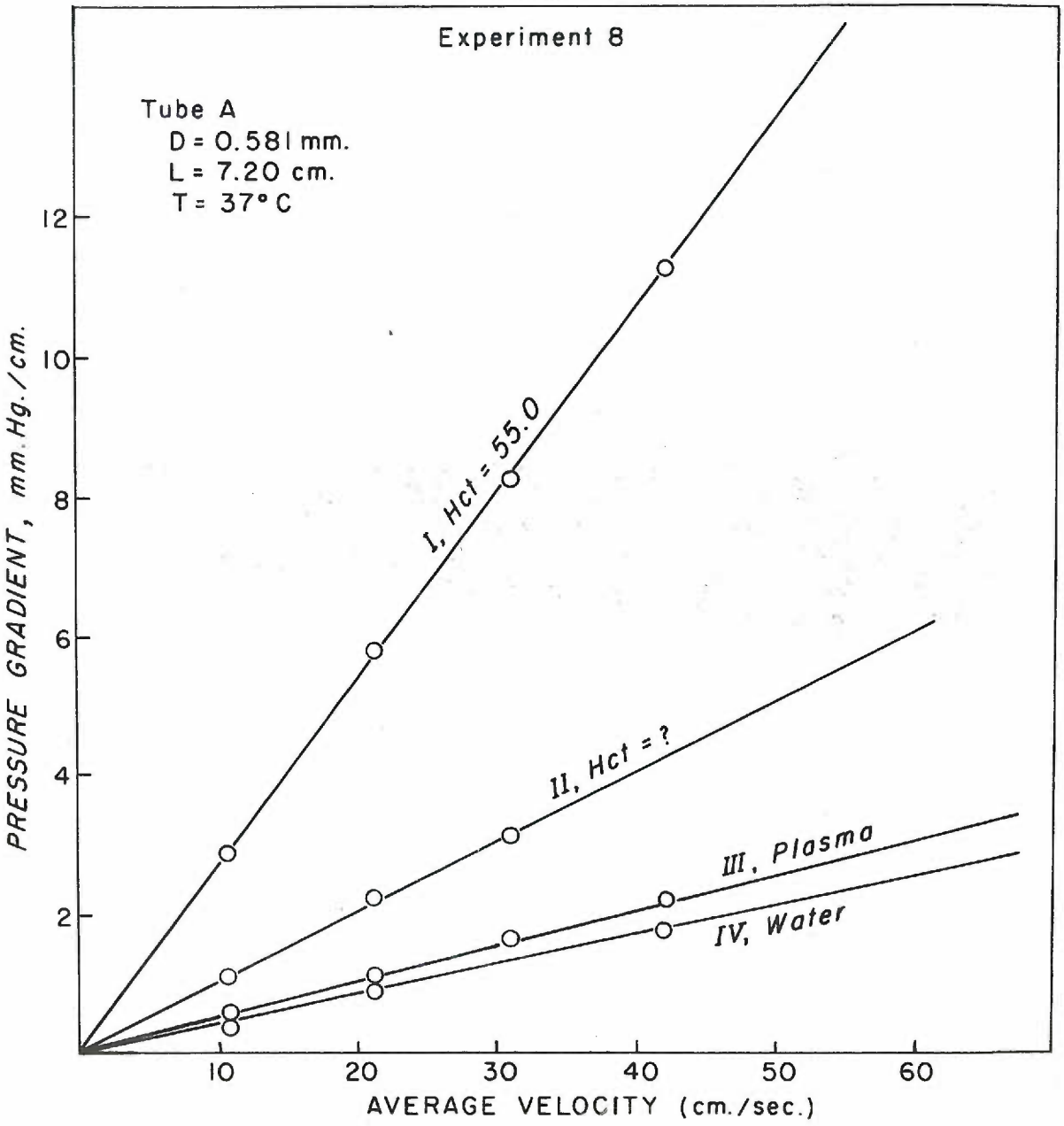
Hypodermic tubing was used in the seven preceding experiments. It was adequate for comparative results. However, the lumen is not visible; hence, there is no way of measuring deviations of the internal diameter, and small particles which may be present in the lumen cannot be seen.

The results obtained in a glass tube 0.581 mm. in diameter are shown in Chart 9. Over a wide velocity range, a linear relation is observed and the intercept is at zero. Blood sample II follows the same pattern, although its hematocrit was not measured.

Chart 9

Pressure-flow data for a water sample, plasma sample, and two blood samples are plotted in this chart. The tube is a precision bore glass tube 0.58 mm. in diameter. Temperature is constant at 36°C. Flow velocity ranges from 10 cm./sec. to 42 cm./sec. and pressure is recorded with a Sanborn manometer.

CHART 9


Experiment 8
Tube A
D = 0.581 mm.
L = 7.20 cm.
T = 37° C
I, Hct = 55.0
II, Hct = ?
III, Plasma
IV, Water
PRESSURE GRADIENT, mm. Hg./cm.
AVERAGE VELOCITY (cm./sec.)
2
4
6
8
10
12
10
20
30
40
50
60

Experiment No. 9: Chart 10; Table 11 and 12

In this experiment a precision bore glass tube 0.338 mm. in diameter was employed. Fresh blood samples were obtained by venipuncture. In Chart 10(a) the results of a fresh blood determination are compared with a water control and an aqueous glycerol control, using the 10 cc. syringe as a blood reservoir. Note that the water control intercepts the pressure axis at minus 0.04 mm. Hg, implying an error of minus 0.3 mm. Hg in recording pressure head. Table 11.

To extend the observed velocity range down even further, two fresh blood samples and a water control were forced through this tube from a tuberculin syringe reservoir. This allowed pressure head measurements at velocities of 6 cm./sec. to 0.6 cm./sec. and the results are presented in Chart 10(b). The same pattern as has been observed before is repeated even at these extremely low linear velocities. Table 12.

Chart 10

(a) Pressure-flow data for water, aqueous glycerol, and blood samples are plotted in this chart. The tubing is a precision bore glass tube 0.338 mm. in diameter. Temperature of flow is constant at 35°C. Average velocity of flow varies from 7 cm./sec. to 66 cm./sec. and pressure is recorded with a Sanborn electromanometer.

(b) The same tube is used in this chart as in Chart 10(a). Temperature of flow is constant at 35°C. The velocity flow has been extended down to 0.6 cm./sec. by employing a tuberculin syringe as a blood reservoir, and the pressure-flow data of two blood samples and a water control are graphed.

CHART 10a

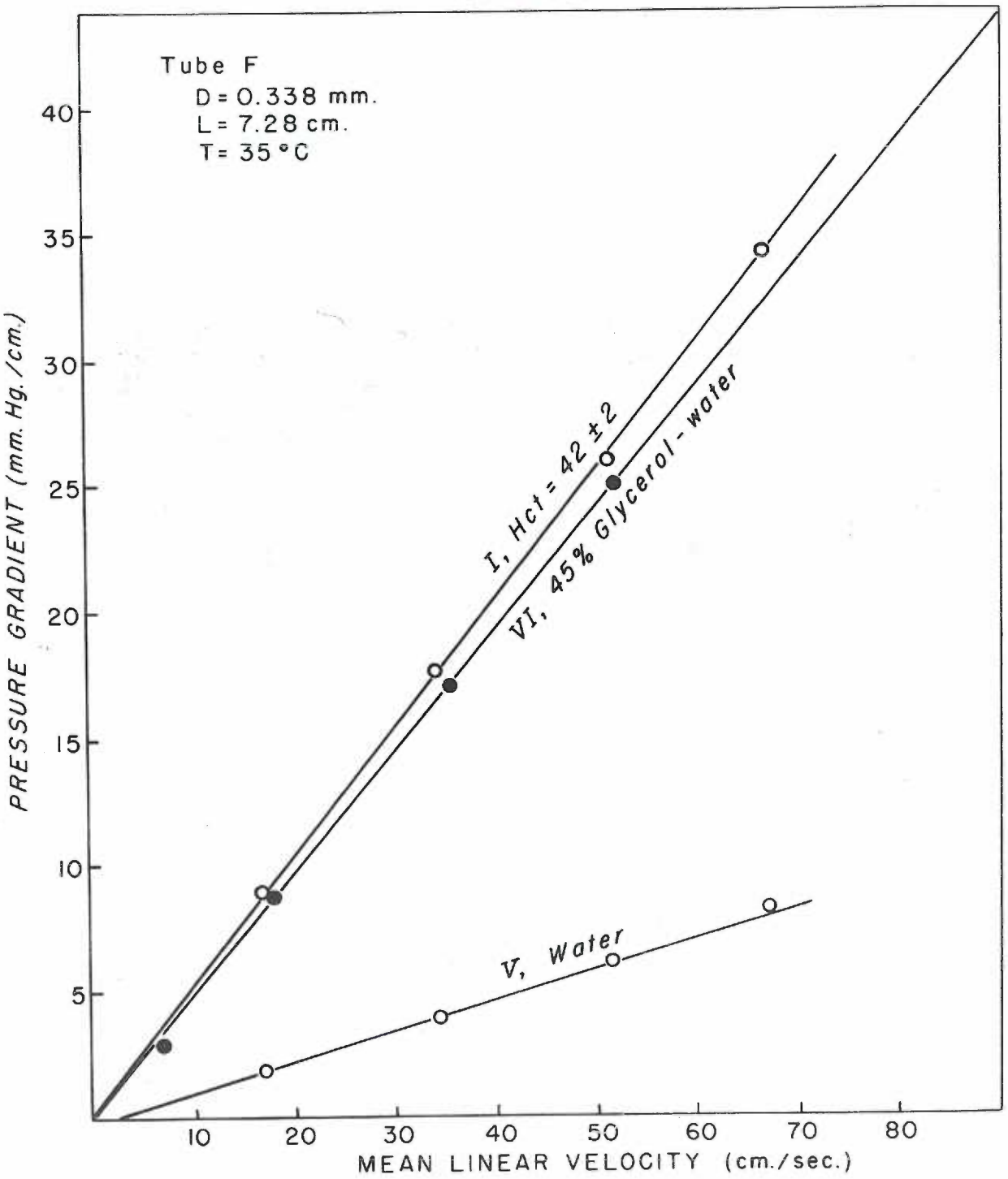
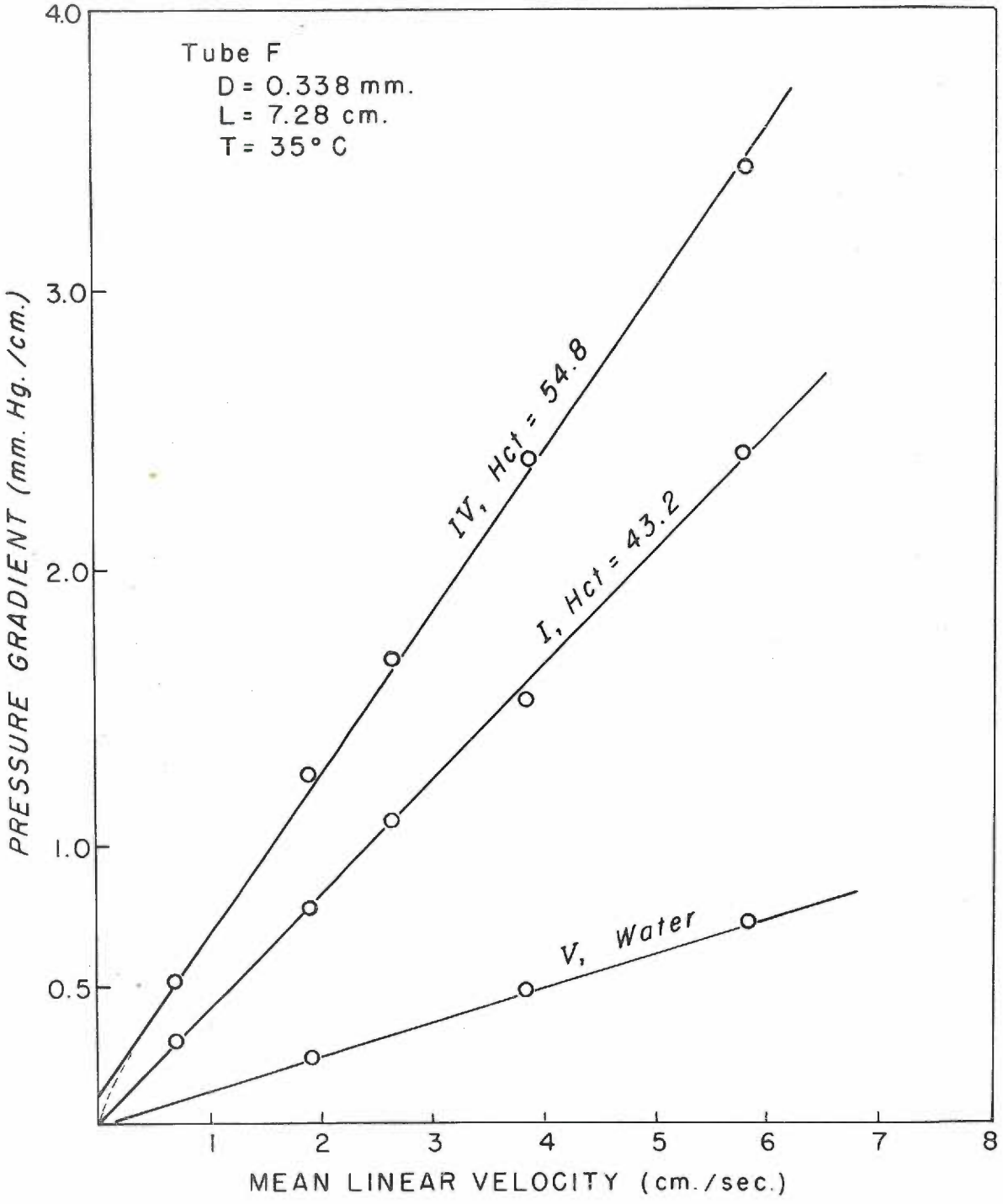

Tube F
D = 0.338 mm.
L = 7.28 cm.
T = 35 °C
I, Hct = 42 ± 2
VI, 45% Glycerol - water
V, Water
PRESSURE GRADIENT (mm. Hg./cm.)
MEAN LINEAR VELOCITY (cm./sec.)
5
10
15
20
25
30
35
40
10
20
30
40
50
60
70
80

CHART 10b


Tube F
D = 0.338 mm.
L = 7.28 cm.
T = 35° C
IV, Hct = 54.8
I, Hct = 43.2
V, Water
PRESSURE GRADIENT (mm. Hg./cm.)
MEAN LINEAR VELOCITY (cm./sec.)
4.0
3.0
2.0
1.0
0.5
1
2
3
4
5
6
7
8

Experiment No. 10: Chart 11 (a and b); Table 13

Since no glass capillary tubes under 0.3 mm. could be supplied, and since the hypodermic tubing of 0.2 mm. diameter was not sufficiently accurate in bore, a technique was devised of directly measuring blood flow in smaller capillary tubes by an indirect approach. It will be described in detail for this experiment only (Figure 3).

A piece of soft glass tubing 1.0 mm. in internal diameter is heated over a Bunsen flame and drawn out to a given length, producing a long tapered approach to a narrow capillary tubing, whose diameter is relatively constant for only a short length. The tube is then broken and the large end filed smooth to fit a brass adapter for a Luer-Lok connection. Water and blood pressure heads are measured in this tube, (Ia), as in preceding experiments, and then a distal fragment is filed, broken off and saved. Blood and water pressure heads are then measured in the shortened tube, (Ib), the difference between these results and those in the long tube being contributed by the distal fragment (Iab). The dimensions of this fragment are then determined under a microscope.

A tuberculin syringe was used to deliver blood. The pressure gradients at each dial setting are illustrated in Chart 10(a) for tubes Ia and Ib. From these data, the pressure gradients in tube Iab were calculated and are plotted as a function of volumetric rate of flow. The linear velocity could only be approximated since the bore is not absolutely uniform.

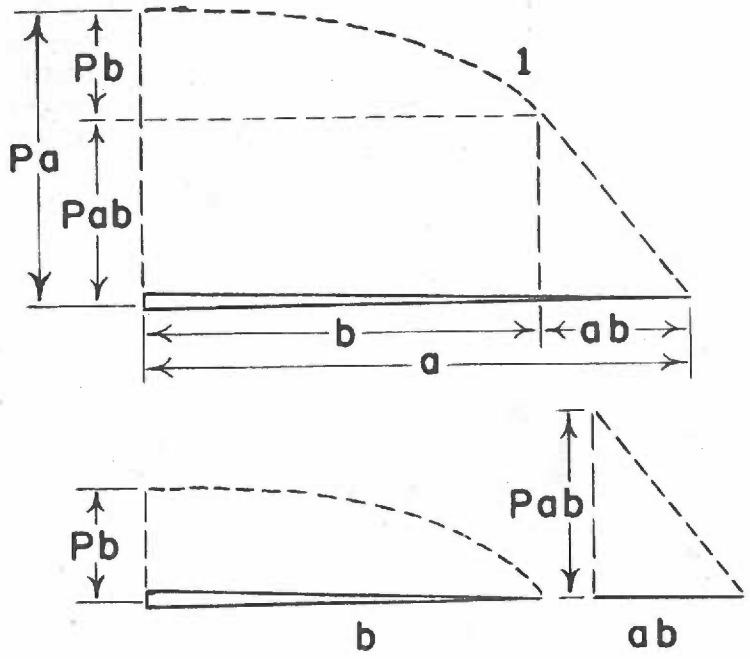
The calculated blood flow and water flow curves in Iab are plotted in Chart 10(b). The same linear relation is observed as in previous experiments.

While the specific viscosity of blood in this experiment is apparently 2.6, which is far below normal for blood of Hct. = 40.7, there is reason to suspect the accuracy of the pressure data for tube Ib, since tube Ib was found to have several small red cell emboli lodged in it at the conclusion of the experiment. The measured diameter of 0.0705 - 0.0980 is sufficiently small to cause large errors in pressure measurement with particles partially occluding the lumen.

Figure 3

This is a schematic drawing of tubes I, III, and V which were constructed in order to extend the diameter range below 0.2 mm. Uniform volumetric rate of flow was established in tube (a). For this flow rate, a pressure head exists which may be represented as P_a. The broken line represents the magnitude of this pressure head at different points along the length of the tube, assuming that it was discharging into the atmosphere. If the fragment (ab) was now removed and the same flow rate reestablished, the pressure head across the remaining tube (b) may be represented as P_b. The pressure head which was effective across tube (ab) may then be calculated by subtracting P_b from P_a.

In our experiments, P_a and P_b were measured directly with a Sanborn manometer at each of several volumetric rates of flow. From the resulting pressure-flow graphs, the pressure head (P_{ab}) across tube (ab) may be determined for any desired volumetric flow rate within the limits which were studied.



AT STEADY FLOW, $Pab = Pa - Pb$

Fig. 3

Chart 11

(a) Pressure-flow graphs for water and a blood sample in tubes I_a and I_b. The tube which was studied is listed on each pressure-flow graph just preceding the sample description. Temperature was constant at 36°C. and pressure was recorded with a Sanborn electromanometer.

(b) Pressure-flow graph for water and blood in tube I_{ab}. The data for this chart were taken from Chart 11(a) as described in the protocol.

CHART II a

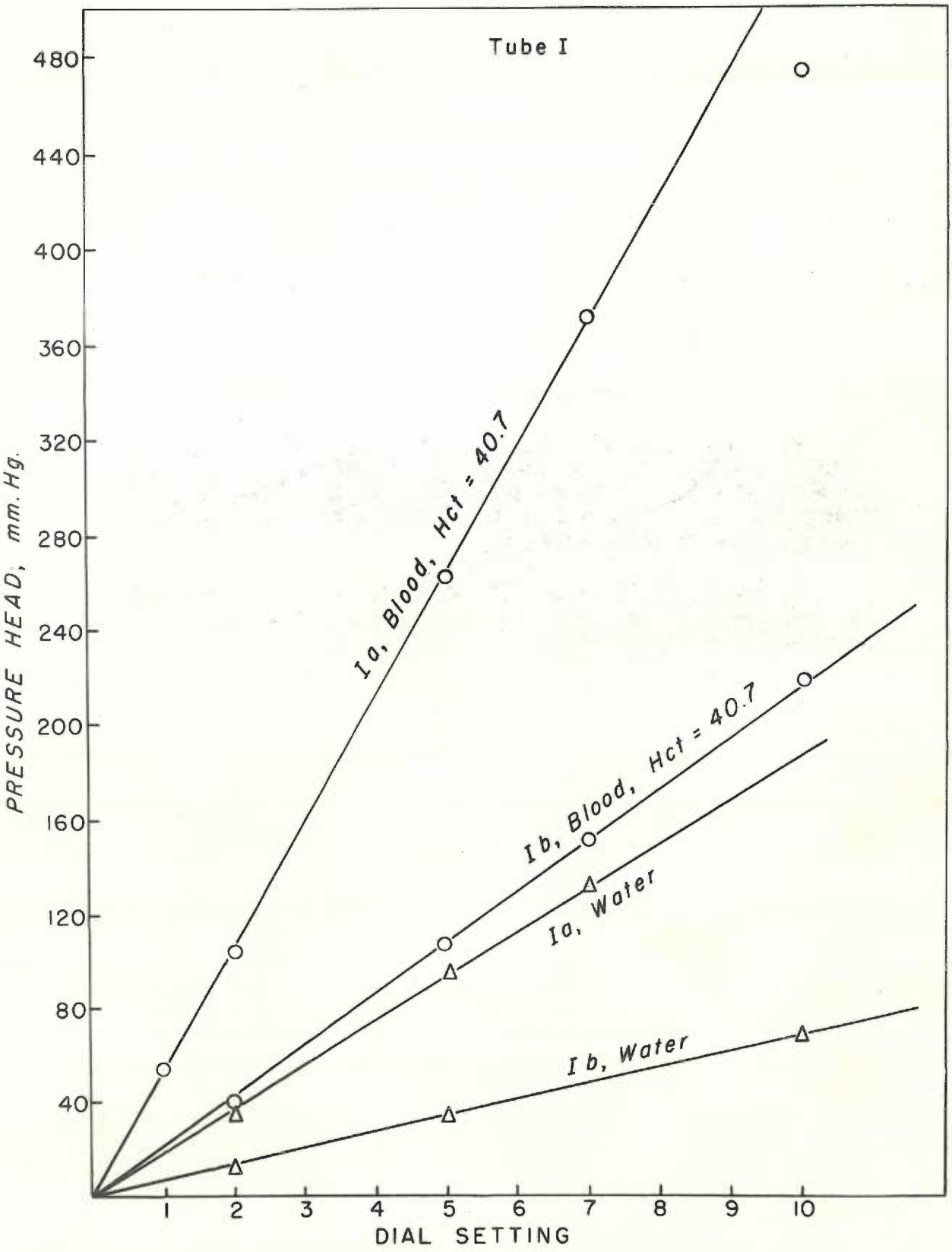
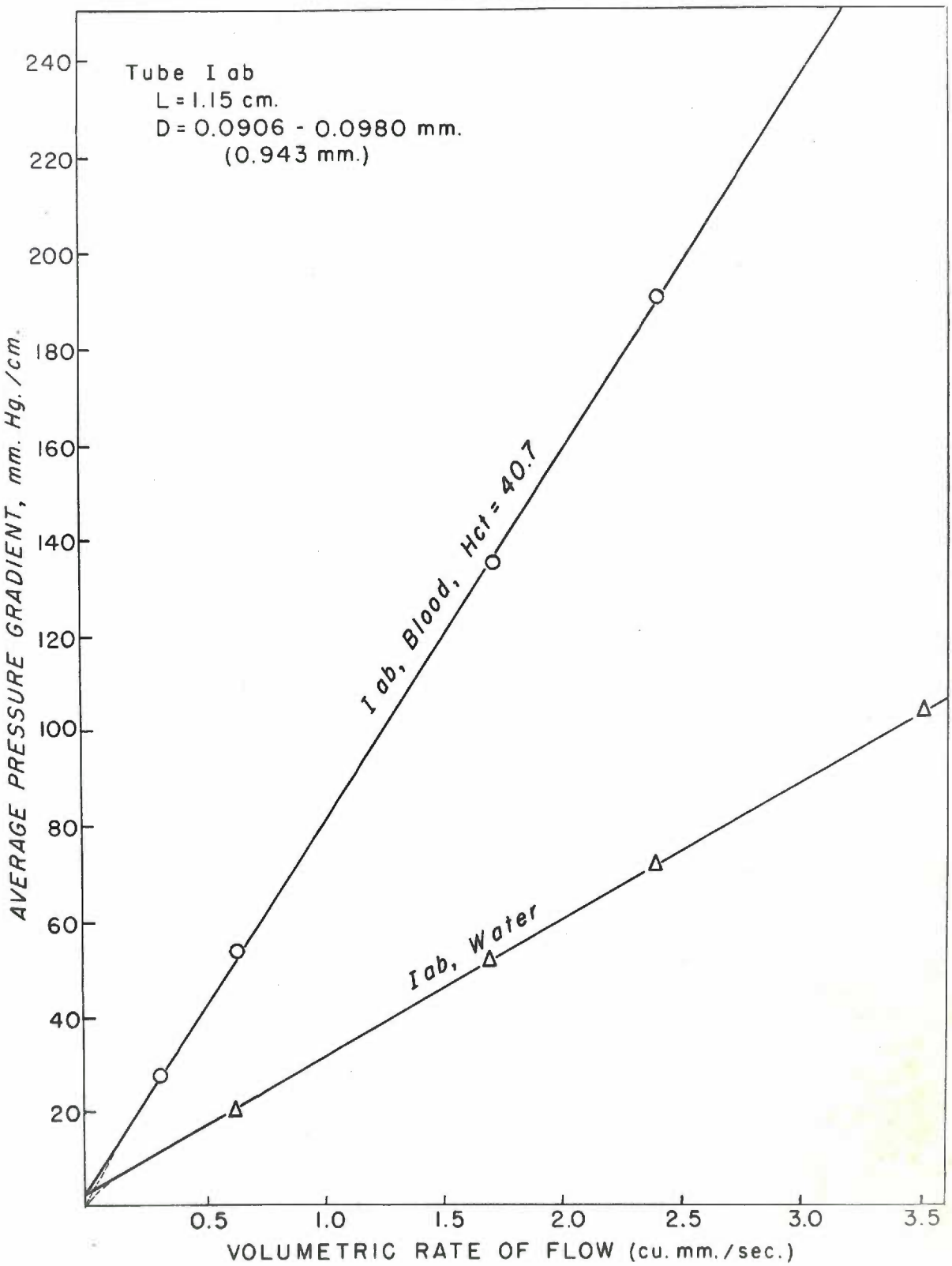

Tube I
480
440
400
360
320
280
240
200
160
120
80
40
PRESSURE HEAD, mm. Hg.
Ia, Blood, Hct = 40.7
Ib, Blood, Hct = 40.7
Ia, Water
Ib, Water
1
2
3
4
5
6
7
8
9
10
DIAL SETTING

CHART II b


Tube I ab
L = 1.15 cm.
D = 0.0906 - 0.0980 mm.
(0.943 mm.)
I ab, Blood, Hct = 40.7
I ab, Water
AVERAGE PRESSURE GRADIENT, mm. Hg./cm.
VOLUMETRIC RATE OF FLOW (cu. mm./sec.)
240
220
200
180
160
140
120
100
80
60
40
20
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Experiment No. 11: Chart 12; Table 14

The tubing in this experiment was prepared by a method identical to that used in Experiment No. 10. The diameter of the distal fragment was measured as 0.105 mm. - 0.110 mm. A fresh blood sample was studied using a tuberculin syringe for delivery, and the Sanborn manometer was used for recording pressure head. The pressure gradient of water flow was determined first in tube III_a (Chart 12a). Heparin solution was then permitted to stand in the flow system for twenty minutes. This was flushed out with 2 cc. of blood before the blood pressure gradients were recorded for tube III_a (Chart 12a). The tube was then filed and fragment III_{ab} was broken off. Pressure gradients for blood flow in tube III_b were determined immediately. Hemosol was used to flush the system of any adherent red cells and the water control in tube III_b was determined (Chart 12a). At the conclusion of the experiment the tube was inspected under the microscope and found free of red cells.

The data for tube III_{ab} were then arranged as before and are summarized in Chart 12(b). Two interesting features are noted. There is a linear pressure-flow relation in this narrow tube which intercepts the axis at zero. Also, there has been no alteration of the specific viscosity (4.7) from that which would be expected in larger tubes.

Chart 12

(a) Pressure-flow graphs for water and a blood sample in tubes III_a and III_b. The lines are described as in the preceding chart. Temperature was constant at 37°C. and pressure was recorded with a Sanborn electromanometer.

(b) Pressure-flow graph for water and a blood sample in tube III_{ab}.

CHART 12a

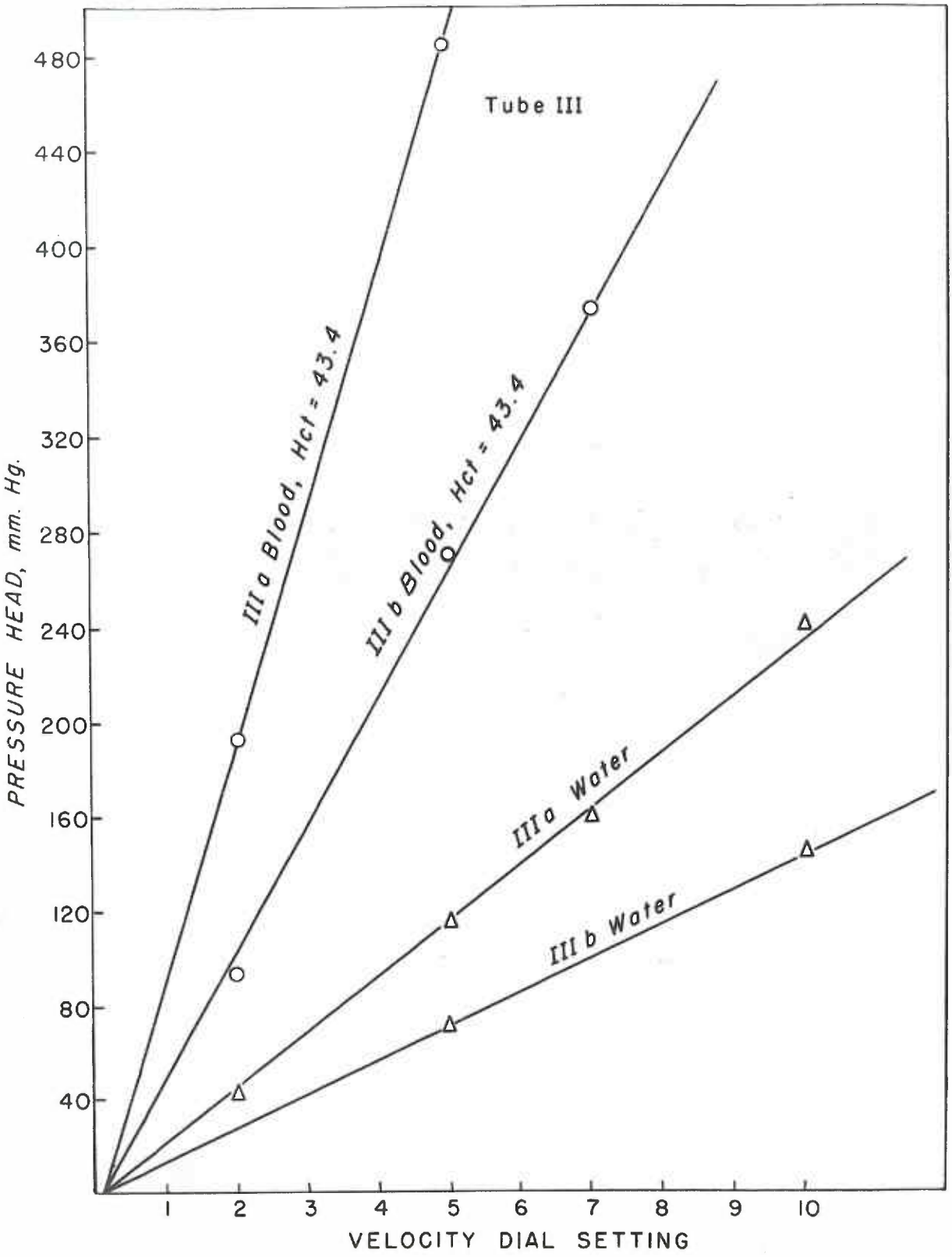
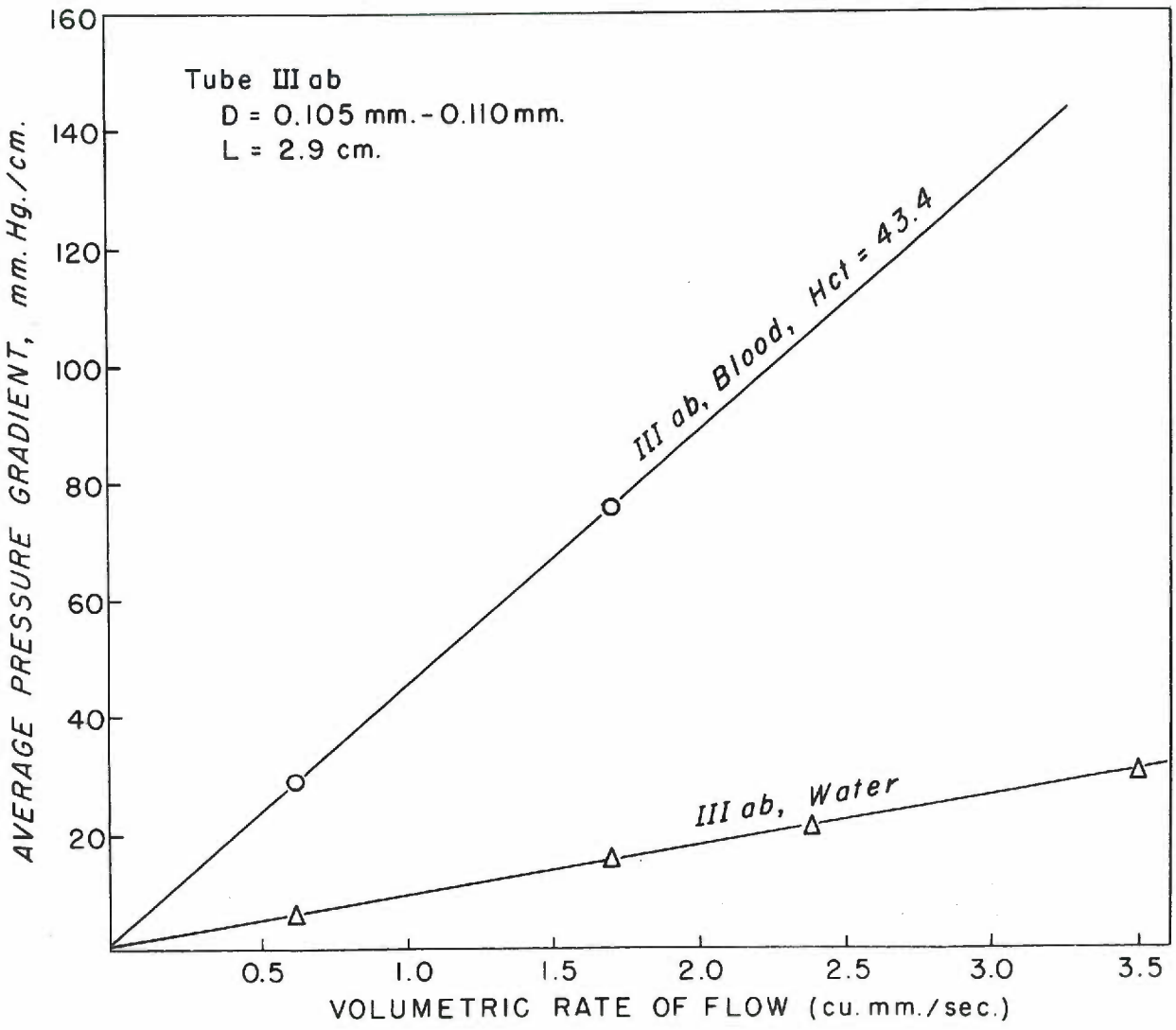

Tube III
III a Blood, Hct = 43.4
III b Blood, Hct = 43.4
III a Water
III b Water
PRESSURE HEAD, mm. Hg.
480
440
400
360
320
280
240
200
160
120
80
40
1
2
3
4
5
6
7
8
9
10
VELOCITY DIAL SETTING

CHART 12b


Tube III ab
D = 0.105 mm. - 0.110 mm.
L = 2.9 cm.
III ab, Blood, Hct = 43.4
III ab, Water
AVERAGE PRESSURE GRADIENT, mm. Hg./cm.
160
140
120
100
80
60
40
20
0.5
1.0
1.5
2.0
2.5
3.0
3.5
VOLUMETRIC RATE OF FLOW (cu. mm./sec.)

Experiment No. 12: Chart 13; Table 15

Another tube was prepared as in Experiment No. 10. The distal fragment in this case was 0.140 mm. - 0.162 mm. in diameter. A fresh blood sample was studied in exactly the same manner as in the last experiment. The results of the blood and water flows in tubes V_a and V_b are diagramed in Chart 13(a). From this chart the data for tube V_{ab} are taken as in the two preceding experiments (Chart 13b).

Again a linear function with a zero intercept is observed. The specific viscosity of this blood sample is 4.8, which constitutes a good check with Experiment No. 11.

Chart 13

(a) Pressure-flow graphs for water and a blood sample in tubes V_a and V_b. The lines are described as in Chart 11. Temperature was constant at 37°C. and pressure was recorded with a Sanborn electromanometer.

(b) Pressure-flow graph for water and blood in tube V_{ab}.

CHART 13a

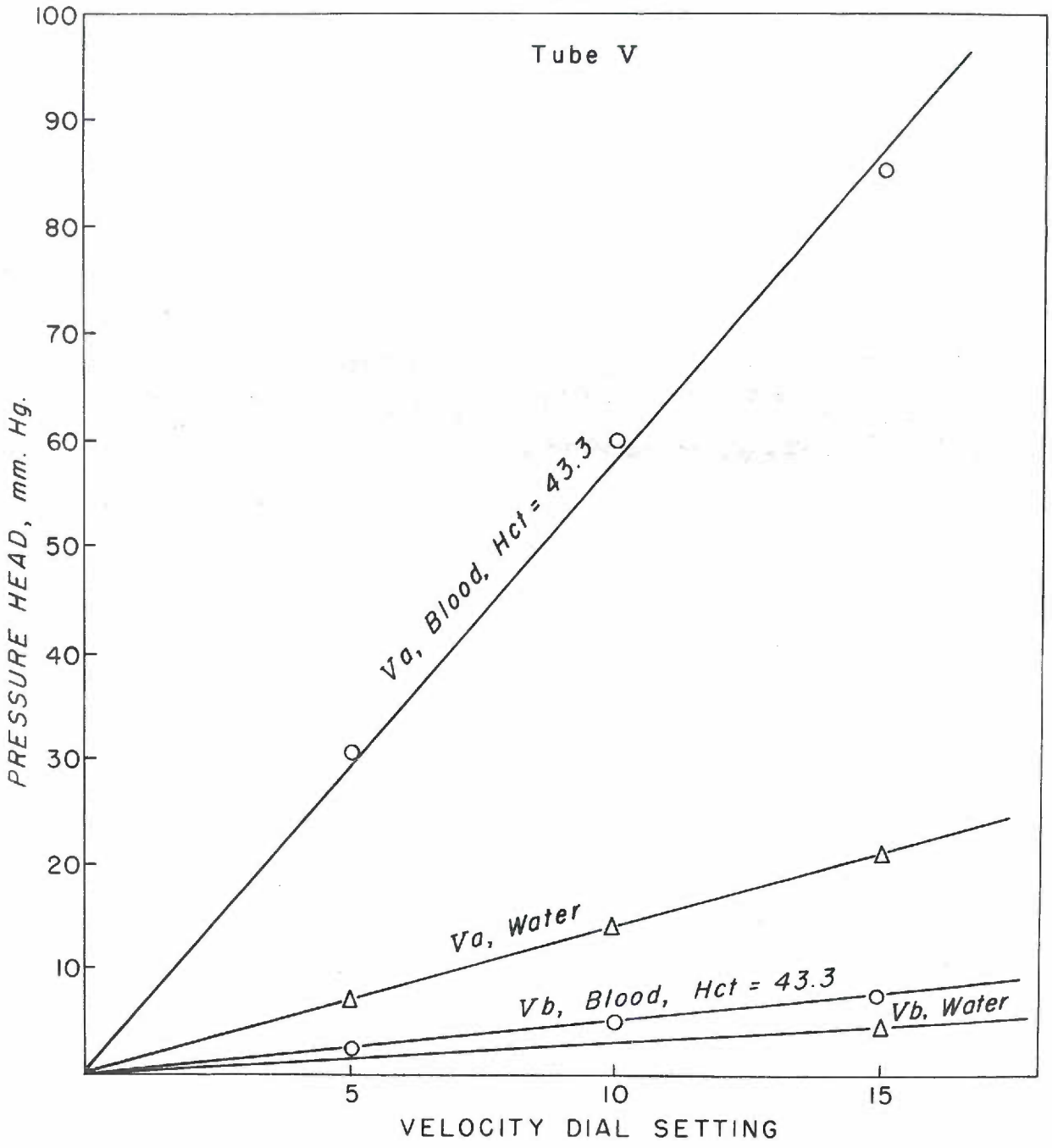
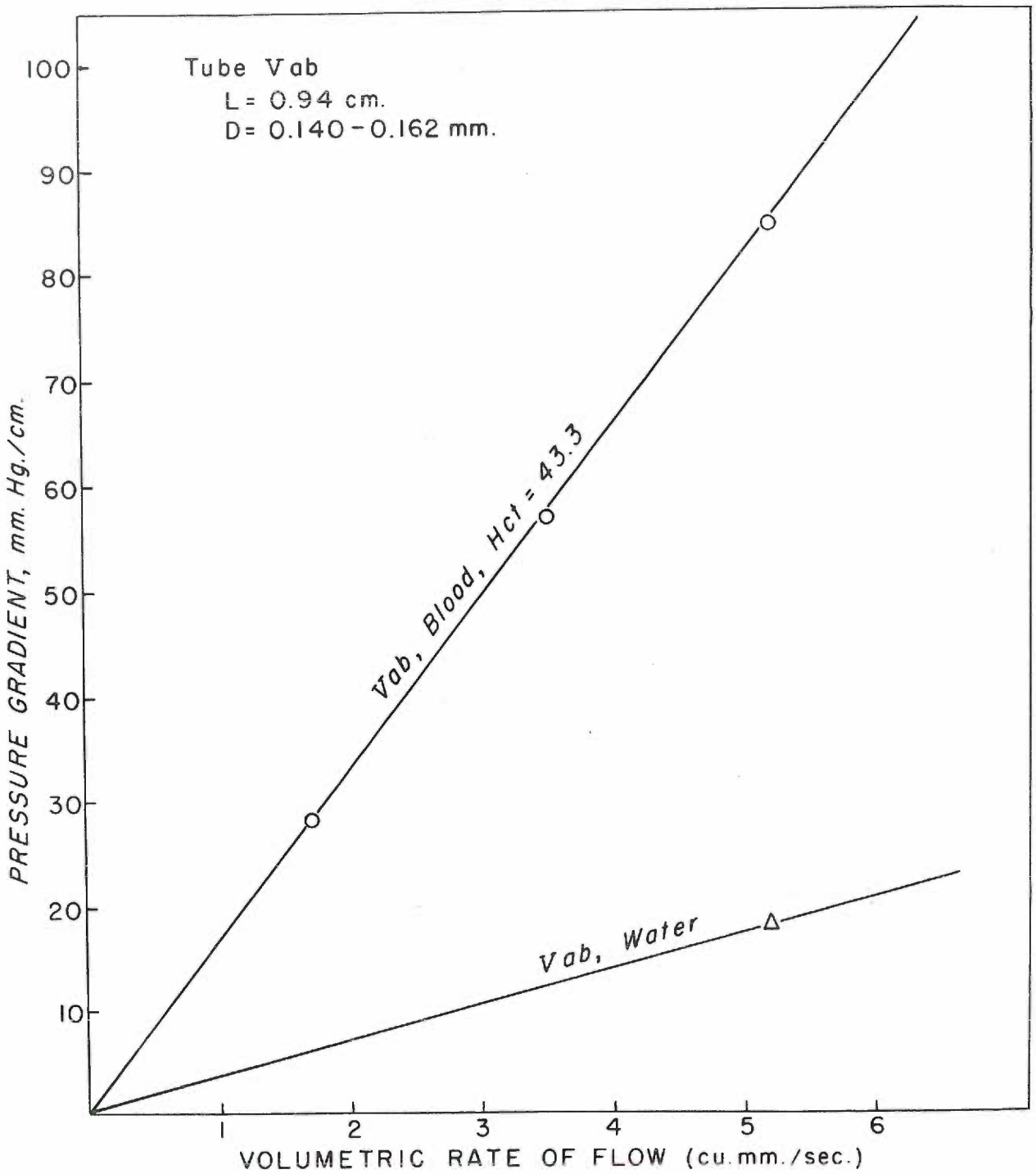

Tube V
PRESSURE HEAD, mm. Hg.
100
90
80
70
60
50
40
30
20
10
Va, Blood, Hct = 43.3
Va, Water
Vb, Blood, Hct = 43.3
Vb, Water
5
10
15
VELOCITY DIAL SETTING

CHART 13 b


Tube Vab
L = 0.94 cm.
D = 0.140 - 0.162 mm.
Vab, Blood, Hct = 43.3
Vab, Water
PRESSURE GRADIENT, mm. Hg./cm.
VOLUMETRIC RATE OF FLOW (cu.mm./sec.)
100
90
80
70
60
50
40
30
20
10
1
2
3
4
5
6

Experiment No. 13: Table 16

Since Fahraeus was rather positive about the mechanism accounting for his observed decrease in specific viscosity, namely, a decrease in hematocrit and a streaming of red cells down the axial core of flow, and since the decrease of specific viscosity has not been observed in this work, it seemed desirable to test his hypothesis. Experiment No. 12 is devised to test the suspension stability of blood flowing in a narrow capillary tube at different linear velocities.

The hematocrits of two 10 cc. blood samples were determined in the usual fashion. Successive volumes were then discharged from a tuberculin syringe through tube IIIb directly into a Wintrobe hematocrit tube. Duplicate runs were performed at each of several volumetric rates of flow. Only half the blood volume contained in the syringe was discharged in this manner; the remainder was discarded. Table 16 summarizes the results. Over a wide range of volumetric flow no significant deviation in the hematocrit of the efflux is observed for either sample.

As an adjunct to this experiment, stroboscopic pictures have been obtained of blood flow in a capillary tube 130 microns in diameter. An example is illustrated in Plate I.

Plate 1

A stroboscopic picture (1/10,000 sec.) of blood flow in a glass capillary tube 130 microns in diameter. The average linear velocity of flow is calculated to be 12-13 cm./sec. and the volumetric rate of flow is 1.66 cu.mm./sec. The picture confirms what has been observed in several other small glass tubes — the red cells are dispersed in random fashion throughout the fluid phase. Only at the extreme periphery of the flowing blood is there a suggestion of a thin (3-7 microns) plasma film which is free of cells.

Summary of Constant Flow Technique.

The results obtained in seven capillary tubes with a diameter range of 0.51 mm. - 0.105 mm. are not in accord with previous literature on two major points. No significant variation in the specific viscosity of blood was observed in any of these tubes as a function of linear velocity of flow. Nor is the specific viscosity significantly affected by a decrease in tube diameter below 0.3 mm. in the low velocity range studied. Evidence is submitted which suggests that in tubes of this size at physiologic velocities of flow blood behaves as a viscous fluid regardless of its red cell content.

Constant Pressure Technique.

In view of the consistent results obtained using the constant rate injector apparatus it would seem to be unnecessary to undertake the same basic inquiry using a different method if it were not for the fact that there is a discrepancy between results reported in the literature and those presented here. Therefore, it was decided to examine a series of blood samples utilizing a constant pressure head as the energy source for flow, since this is the method generally employed, with the hope of determining the basis for the differences in results.

The data are presented in graphic form, as in the preceding section, and tables of untreated data are included in the appendix.

Experiment No. 14: Chart 14; Table 17

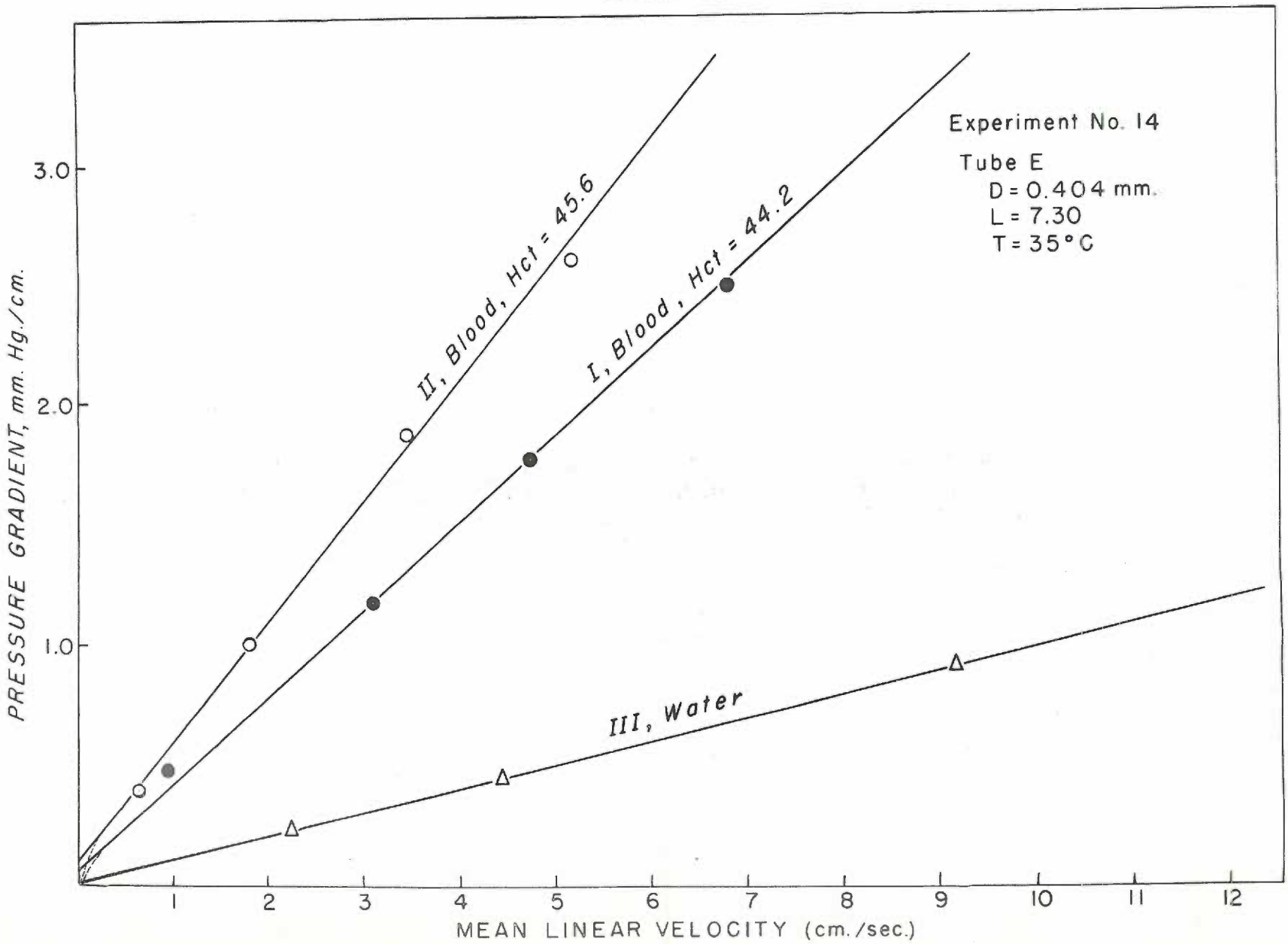
The tube used in this experiment was a precision bore tube, 0.404 mm. in diameter. Blood flow was maintained in this tube between the velocity extremes of 7 cm./sec. to 0.6 cm./sec. by using a water manometer to sustain pressure head. Because of the slow rate of flow, a 200 cu. mm. pipette was used for a blood reservoir. This pipette exerts a capillarity of 18 cm. of water which acts to oppose the pressure head within the air chamber. In addition, the manometer has a capillarity of 10 cm. of water which acts in the same direction as the pipette capillarity. Therefore, 28 cm. of water must be subtracted from each observed pressure head in order to give the actual head which is available to maintain flow. This correction has been made for each observation in the graphs.

Two fresh blood samples were studied and their flow curves are compared with a water control in Chart 15. The same linear relation is observed as described in the first section. Note the intercept of 0.08 mm. Hg.

Chart 14

Pressure flow data are graphed for a water control and two blood samples. A precision bore glass tube was used and temperature of flow was constant at 35°C. Pressure head was supplied by a water manometer.

CHART 14


Experiment No. 14
Tube E
D = 0.404 mm.
L = 7.30
T = 35° C
II, Blood, Hct = 45.6
I, Blood, Hct = 44.2
III, Water
PRESSURE GRADIENT, mm. Hg./cm.
3.0
2.0
1.0
1
2
3
4
5
6
7
8
9
10
11
12
MEAN LINEAR VELOCITY (cm./sec.)

Experiment No. 15: Chart 15; Tables 18 and 19

The flow of four blood samples was studied in a glass tube of 0.338 mm. in diameter. Three of these samples (Hct. 45.2, 38.05, and 38) utilized the water manometer as a source of pressure head. The velocities ranged from 7 cm./sec. to 0.7 cm./sec. for this group and over this range a linear relation was observed between pressure and flow.

The fourth sample had a hematocrit of 60.6. It was a fresh blood sample from which the plasma had been withdrawn after forty minutes of sedimentation had occurred. When the water manometer was used to supply the pressure head, the flow was so prolonged that considerable sedimentation was observed in the blood reservoir. Therefore, a mercury manometer was substituted which extended the maximum attainable pressure head from 300 mm. water to 300 mm. Hg. Under this increased pressure head, the velocity of flow extended from 9.3 cm./sec. to 3.9 cm./sec., which is in the same range as the other three samples. The flow curve for this sample is compared with those of the other bloods in Chart 16(a) and is reproduced in Chart 16(b) on a more suitable scale.

At the same pressure head the velocity of flow of blood sample I is less than half that attained by the other samples, and errors in technique could easily arise due to clot formation or red cell sedimentation. By adjusting the pressure head to give the same linear velocity of flow, these objections are largely overcome.

Chart 15

(a) Pressure-flow data are graphed for a water control and four blood samples in a precision bore glass tube. Temperature of flow was constant at 35°C. and pressure head was supplied by a water manometer for all samples except blood V.

(b) Pressure-flow data for blood sample V are plotted and compared with water flow data. The same tube was used as in Chart (a); however, a mercury manometer was used to supply the pressure head.

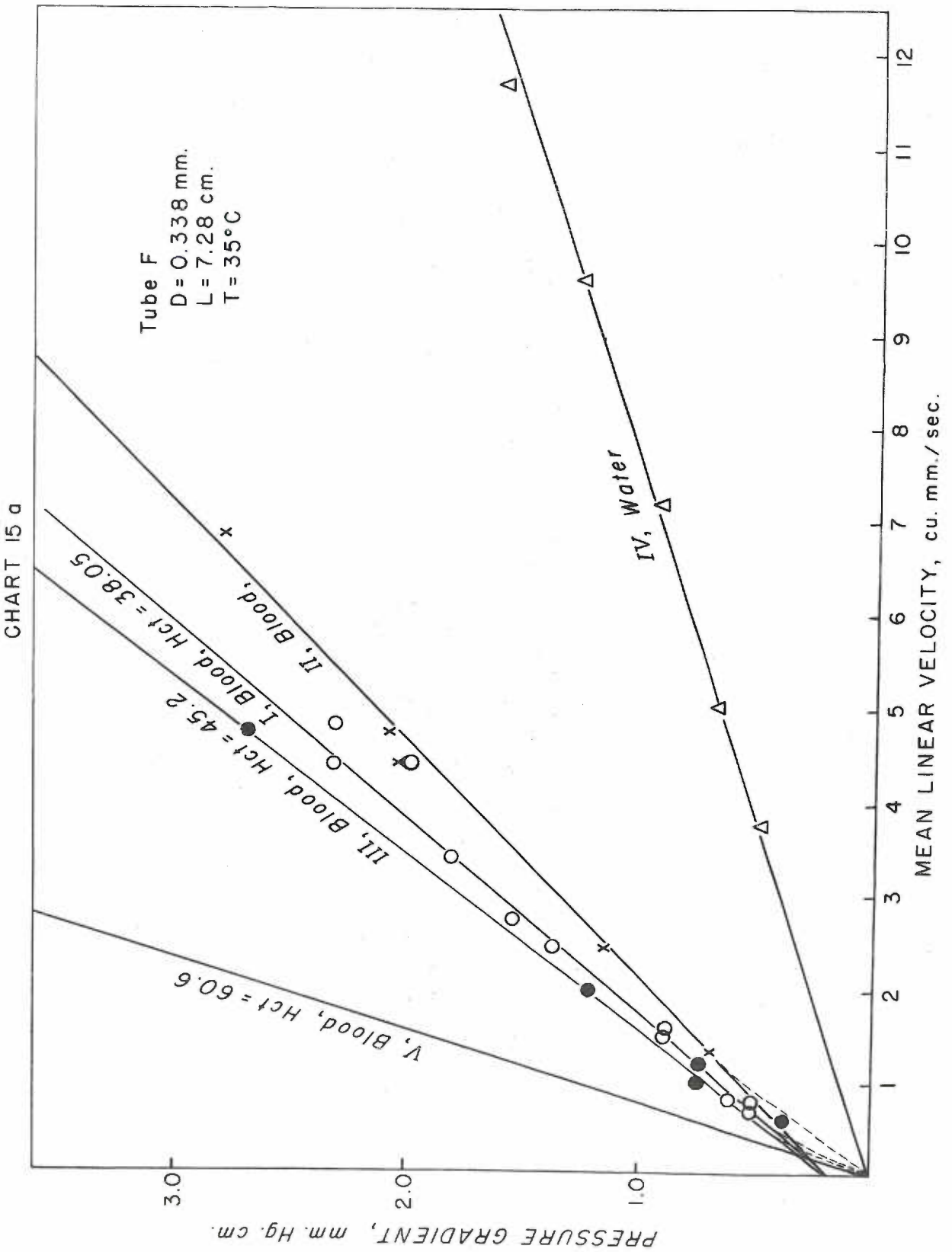
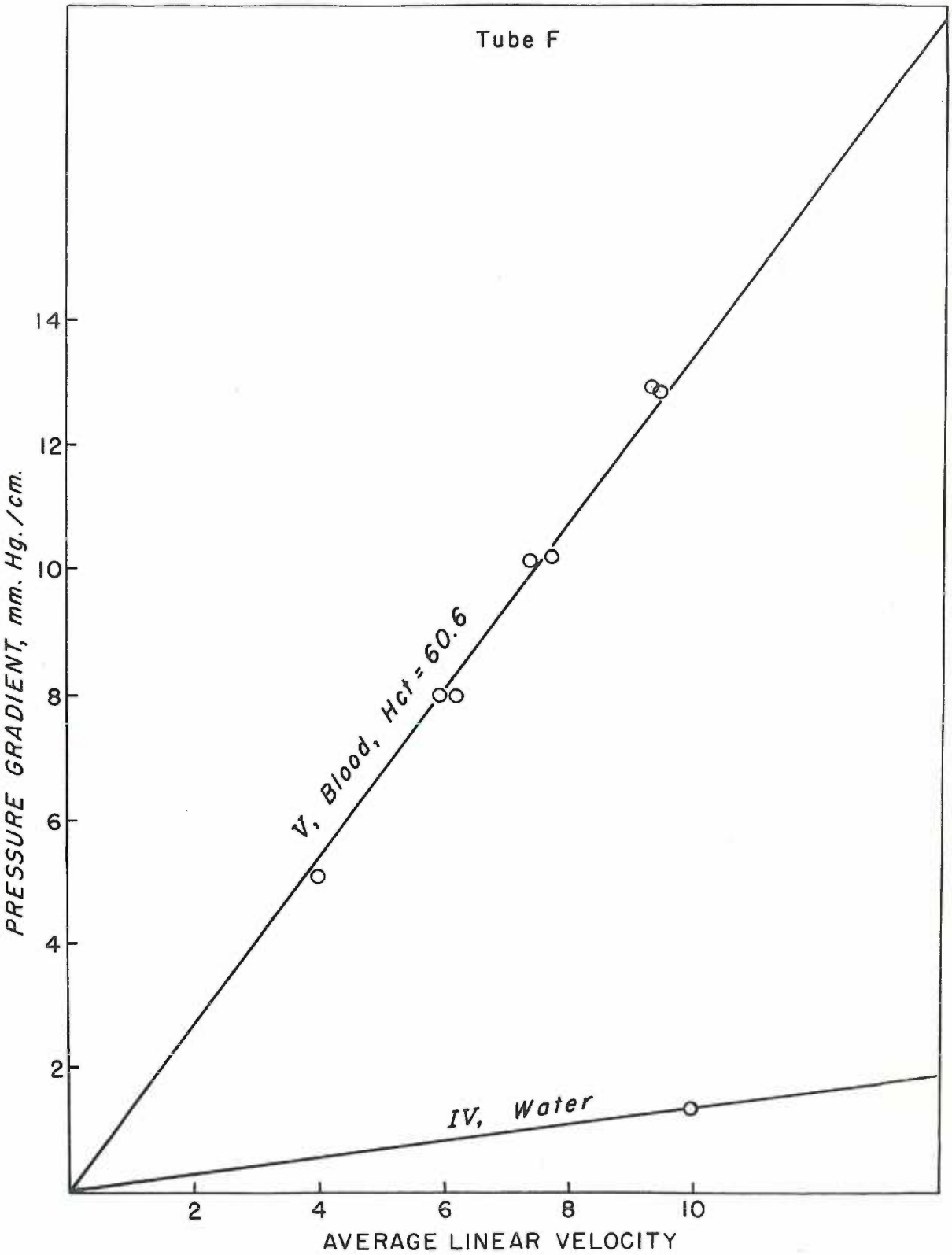


CHART 15 a
Tube F
D = 0.338 mm.
L = 7.28 cm.
T = 35°C
II, Blood,
I, Blood, Hct = 38.05
III, Blood, Hct = 45.2
V, Blood, Hct = 60.6
IV, Water
PRESSURE GRADIENT, mm. Hg. cm.
MEAN LINEAR VELOCITY, cu. mm./sec.
1.0
2.0
3.0
1
2
3
4
5
6
7
8
9
10
11
12

CHART 15 b


Tube F
PRESSURE GRADIENT, mm. Hg. / cm.
14
12
10
8
6
4
2
V, Blood, Hct = 60.6
IV, Water
2
4
6
8
10
AVERAGE LINEAR VELOCITY

Experiment No. 16: Chart 16; Table 20

The smallest precision bore glass tube which could be supplied was 0.309 mm. in diameter. In this experiment three fresh blood samples of normal hematocrit were studied in this tube using the water manometer to supply pressure head.

The results plotted in Chart 17 follow the same pattern as has been observed before. However, in a tube this small, the velocity range is limited when using the water manometer. Because of this the mercury manometer has been used in the final two experiments.

Chart 16

Pressure-flow data are plotted for a water control and three blood samples in a precision bore glass tube. Temperature of flow was constant at 35°C. and the pressure head was supplied by a water manometer.

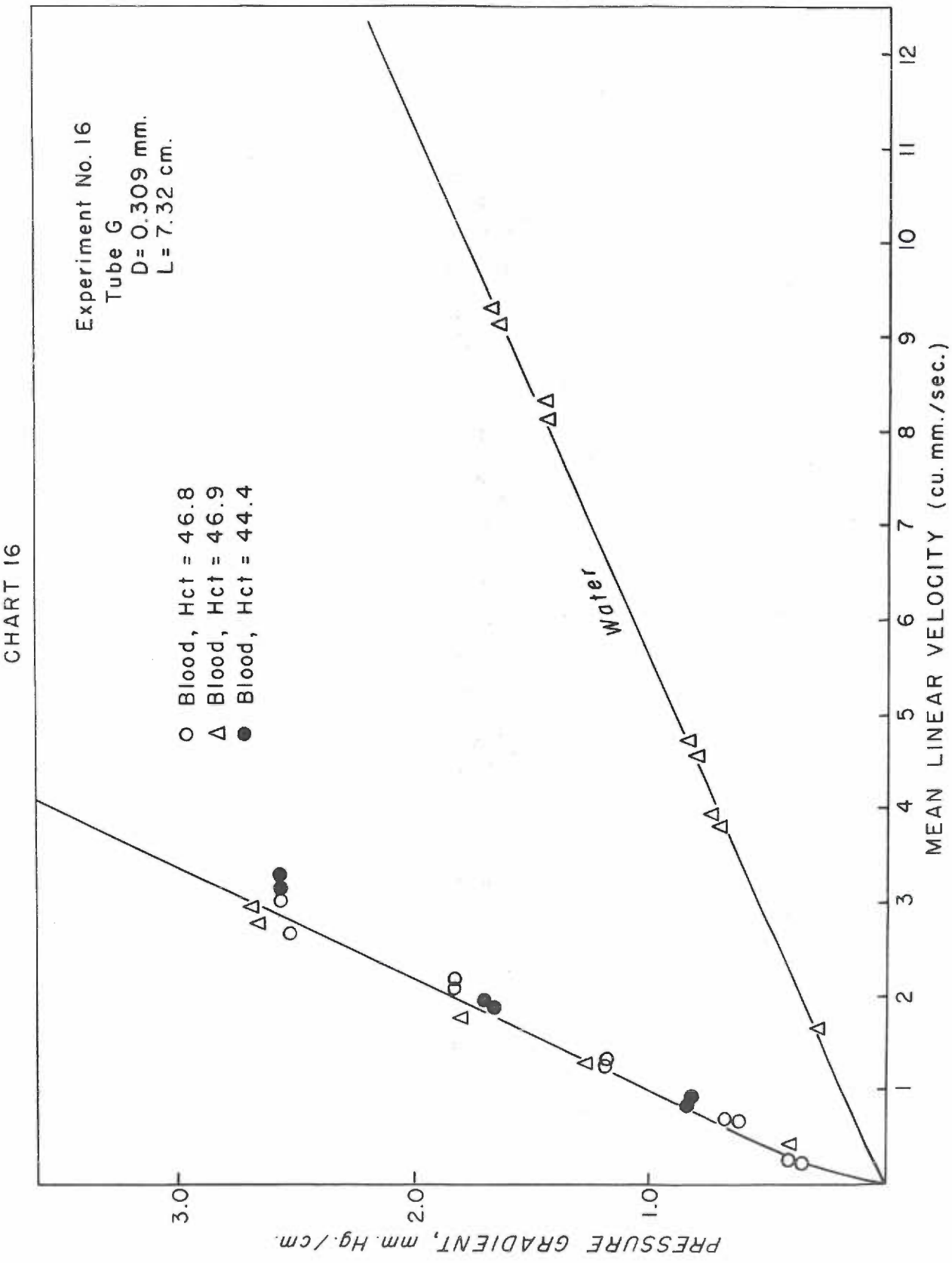


CHART 16
Experiment No. 16
Tube G
D= 0.309 mm.
L= 7.32 cm.
○ Blood, Hct = 46.8
△ Blood, Hct = 46.9
● Blood, Hct = 44.4
Water
PRESSURE GRADIENT, mm. Hg./cm.
3.0
2.0
1.0
1
2
3
4
5
6
7
8
9
10
11
12
MEAN LINEAR VELOCITY (cu. mm./sec.)

Experiment No. 17: Chart 17; Table 21

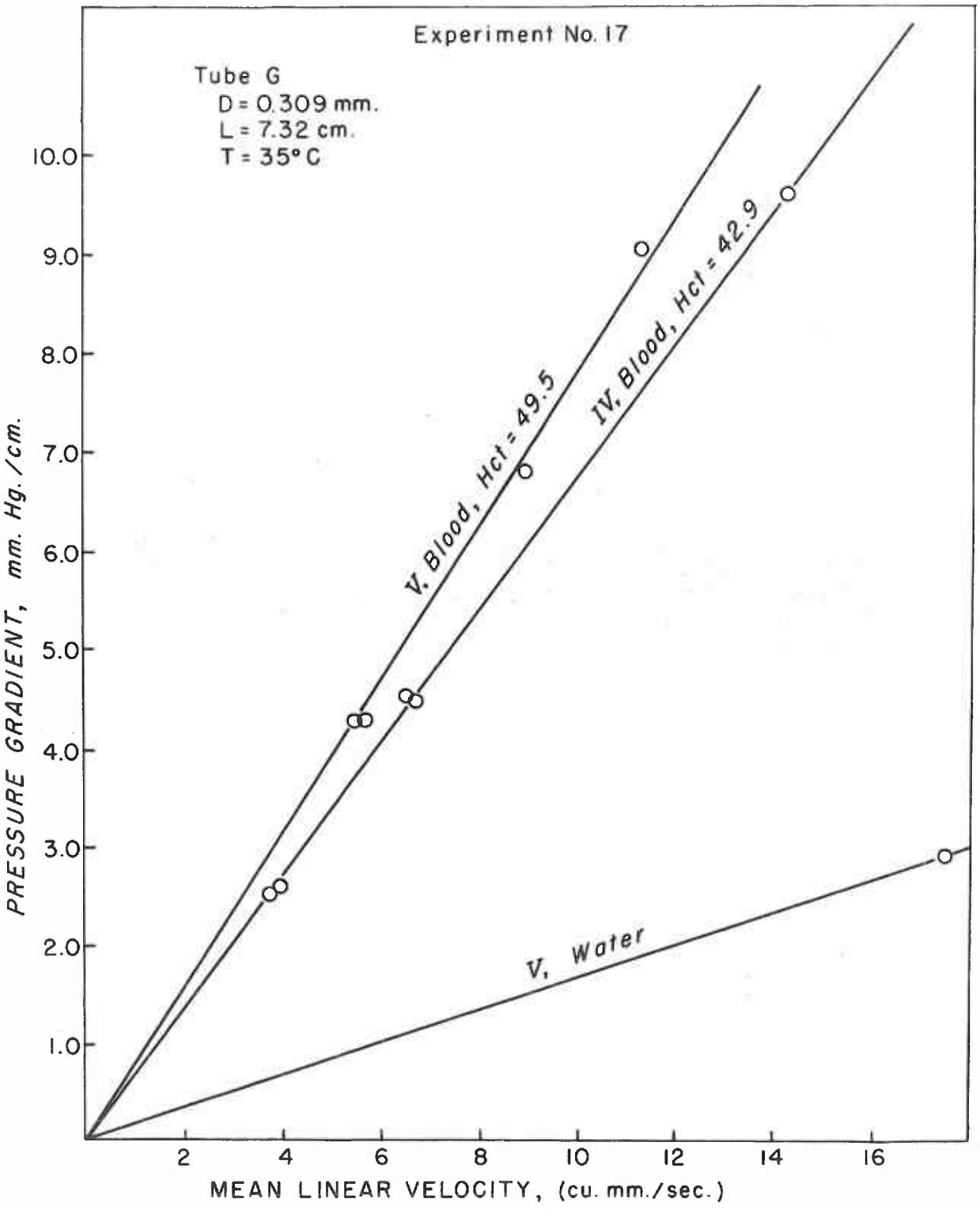
Two fresh blood samples, one of normal hematocrit and one slightly elevated, were forced through the narrowest precision bore tube under a head of pressure supplied by the mercury manometer. Duplicate runs were made in each instance.

The results are plotted in Chart 18. The average velocity of blood flow is extended up to 14 cm./sec. by use of this manometer. The graphs are linear and have a zero intercept.

Chart 17

Pressure-flow data are plotted for a water control and two blood samples in the same tube as was employed in Chart 16. A mercury manometer was used to supply the pressure head; otherwise, the flow conditions are identical with those in Chart 16.

CHART 17


Experiment No. 17
Tube G
D = 0.309 mm.
L = 7.32 cm.
T = 35° C
V, Blood, Hct = 49.5
IV, Blood, Hct = 42.9
V, Water
PRESSURE GRADIENT, mm. Hg./cm.
MEAN LINEAR VELOCITY, (cu. mm./sec.)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
2
4
6
8
10
12
14
16

Experiment No. 18: Chart 18; Table 22

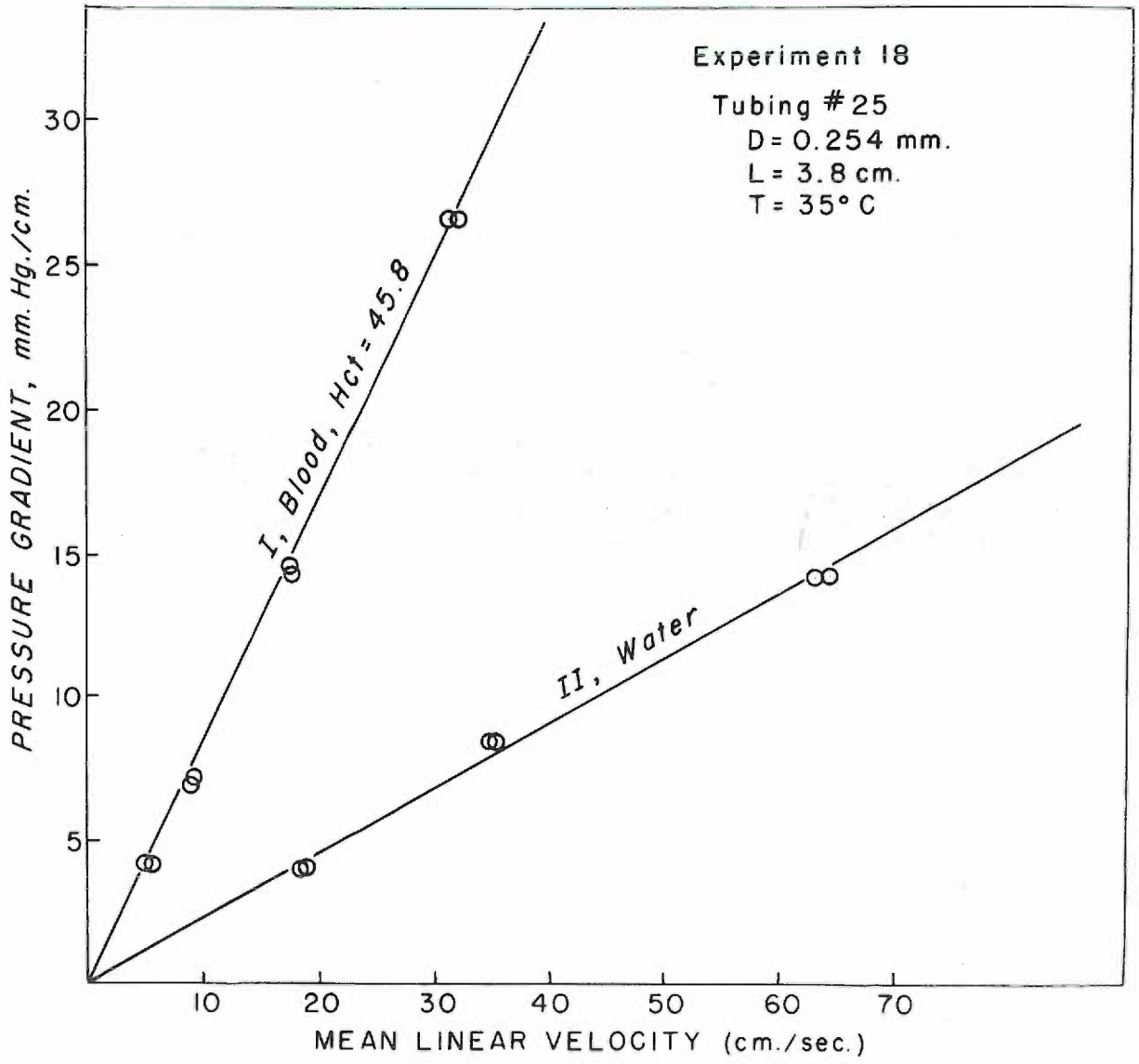
Since no glass tubing under 0.309 mm. was obtainable, hypodermic tubing was used to extend the range down to 0.25 mm. diameter. This was the same tube used in Experiment No. 6. In the present experiment, the mercury manometer was used to supply the pressure head, whereas in Experiment No. 6 the pressure head was recorded by the Sanborn manometer. It is noted that the velocity-pressure curve for water is superimposed in the two experiments, constituting a check on the accuracy of the measurements.

One sample of fresh blood was studied. The 200 cu. mm. pipette was used as in previous experiments and duplicate determinations of flow were made at each pressure head. As may be seen in Chart 19, the pressure-flow relation is linear and has a zero intercept, which confirms the results obtained using the constant flow technique for this tube.

Chart 18

Pressure-flow graphs of a water and blood sample are shown in this chart. The tubing was 0.25 mm. in diameter, temperature was 35°C. and the pressure head was supplied by a mercury manometer. All determinations are in duplicate.

CHART 18


Experiment 18
Tubing #25
D = 0.254 mm.
L = 3.8 cm.
T = 35° C
I, Blood, Hct = 45.8
II, Water
PRESSURE GRADIENT, mm. Hg./cm.
30
25
20
15
10
5
10
20
30
40
50
60
70
MEAN LINEAR VELOCITY (cm./sec.)

Summary of Constant Pressure Technique:

In all instances where flow and pressure were carefully controlled, a linear relation has been observed between the two variables over a physiologic velocity range in tubes which vary in diameter from 0.404 mm. to 0.25 mm. The intercept of this line has not always been exactly at zero, but the deviation is no greater than plus 0.2 mm. Hg. In those instances where the mercury manometer was employed to maintain pressure head the intercept was always at zero, however.

The Law of Diameters.

In view of the findings in the first section of this work, the validity of the law of diameters would be predicted for blood flow. According to this law, the pressure gradients of flow should vary in inverse proportion to the fourth power of the diameter, other factors being constant; or, the volumetric rate of flow should vary in direct proportion to the fourth power of the diameter, other factors remaining constant. Both possibilities have been tested with either a water control or an aqueous glycerol control in standard gauge hypodermic tubing. Blood samples have then been tested in the same tubing and their behavior compared with that of the control fluids. Data are plotted with the abscissa representing the diameter of the tube in mm. (manufacturer's statement) while the ordinate represents either the pressure gradient or the volumetric rate of flow. Tables of untreated data are included in the appendix.

Experiment No. 19: Chart 19; Table 23

In this experiment hypodermic tubing was chosen which covered a diameter range from 0.8 mm. to 0.25 mm. The constant rate injector apparatus was used with a 20 cc. syringe and the Sanborn electromanometer recorded pressure head.

An arbitrary pressure head was chosen for the entire experiment. Since each tube was of equal length, this assured a constant pressure gradient in each tubing. Volumetric flow was varied until this pressure head was achieved, and the flow was then calculated from the standard flow curves for the 20 cc. syringe. A single blood sample was used throughout the experiment. As a control, distilled water was used in similar experiments.

The results are summarized in Chart 19. The results show deviations from the calculated curves but both the control and the blood sample behave similarly and this is most likely due to an error in the stated diameter of the tubing. In calculating the theoretical curve the stated diameter in the smallest tube was taken as a reference.

Chart 19

The volumetric rate of flow of a water sample and a blood sample is plotted as a function of tubular diameter in this chart. Pressure is kept constant in both determinations at 2.0 mm.Hg/cm. of tubular length. The observed curves are plotted as broken lines.

A theoretical curve, based on Poiseuille's Law of Diameters, has been plotted for each sample. The reference data for calculating this curve were taken from the flow rates in the smallest tube. Both the control and the blood sample deviate from this theoretical curve in the same direction and by the same percentage.

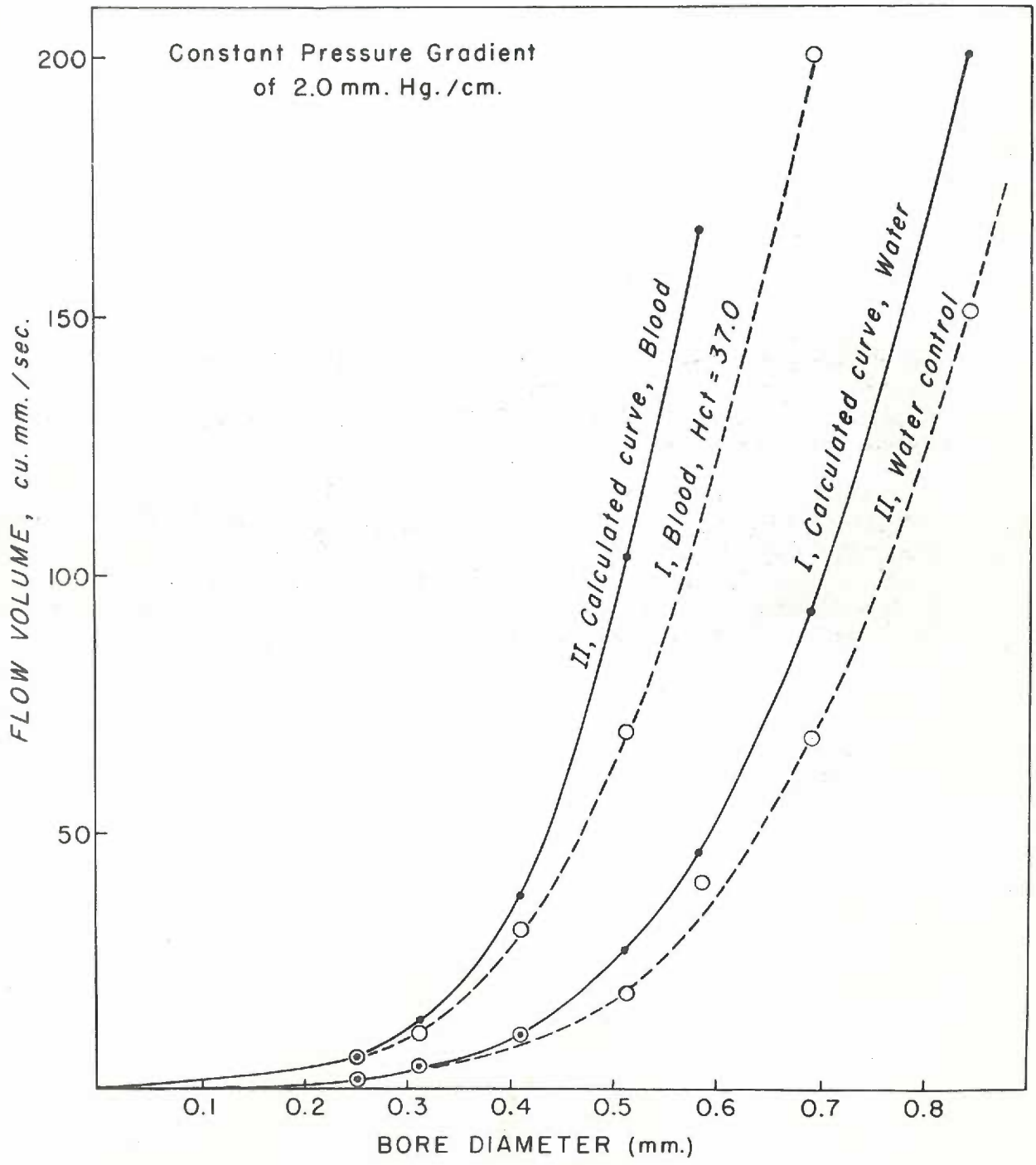
Erratum:

The labelling of each pair of curves in Chart 19 has been reversed. The curves from left to right should read as follows:

II, Calculated curve, Water.
II, Water Control.
I, Calculated curve, Blood.
I, Blood, Hct=37.0.

The data as listed in Table 23 are correct.

CHART 19


Constant Pressure Gradient
of 2.0 mm. Hg./cm.
200
150
100
50
FLOW VOLUME, cu. mm./sec.
II, Calculated curve, Blood
I, Blood, Hct = 37.0
I, Calculated curve, Water
II, Water control
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
BORE DIAMETER (mm.)

Experiment No. 20: Chart 20; Table 24

A constant volumetric rate of flow (10.4 cu.mm./sec.) was maintained for each determination in this experiment. Pressure head was recorded with a Sanborn electromanometer. Three blood samples and an aqueous glycerol control were studied in each of five hypodermic tubes ranging in diameter from 0.58 mm. to 0.20 mm. The tube 0.4 mm. in diameter was found to be defective after the experiment, but the data are included.

The blood was obtained from a freshly collected Red Cross lot and serial dilutions were made with plasma to obtain hematocrits of 43, 33, and 24.

Chart 20 illustrates the results. For each blood sample a series of pressure gradients is observed, depending upon the diameter of the tube and the hematocrit. The data for both the blood samples and the aqueous glycerol control have been compared to the theoretic curves derived from Poiseuille's Law. For the construction of these curves, the stated diameter of the smallest tube has been used as a reference.

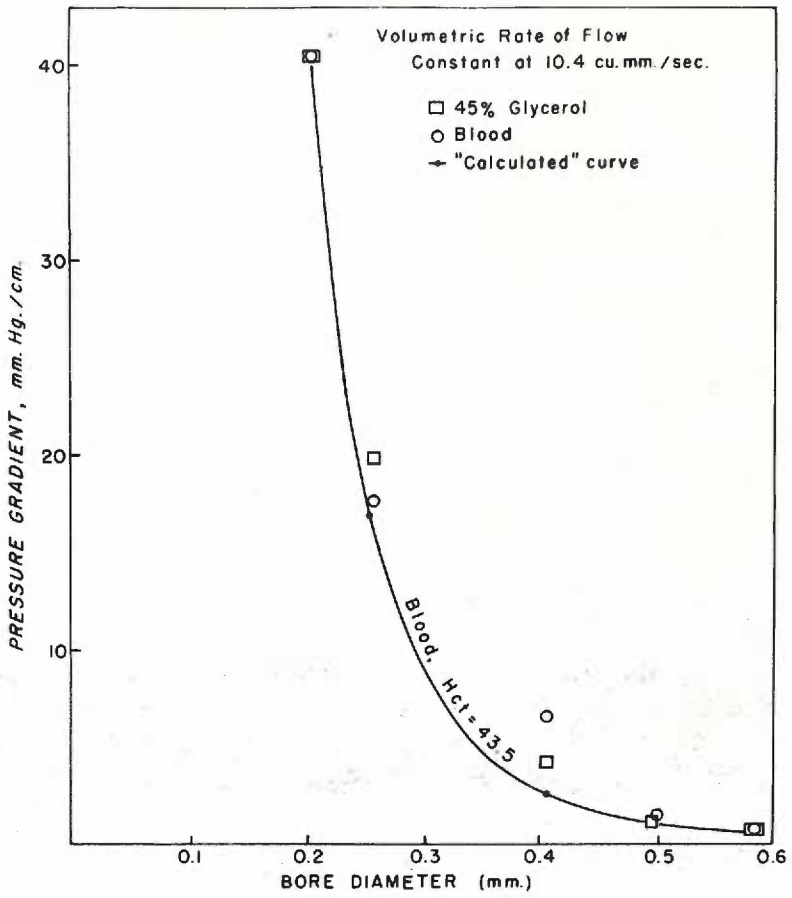
As in Experiment No. 19, the control is observed to deviate from the ideal curve, indicating an error in stated diameter. The blood samples deviate from this curve in the same direction as the control and by the same per cent.

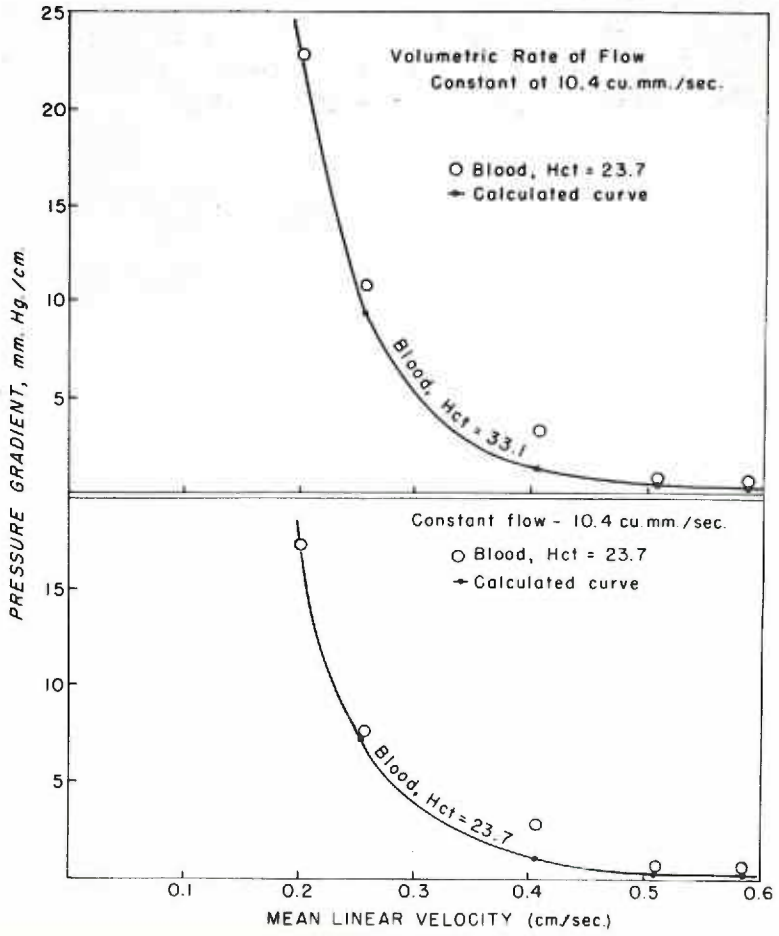
Chart 20

In this chart, the pressure gradient of each of three blood samples is plotted as a function of the tubular diameter. Volumetric rate of flow was maintained at 10.4 cu.mm./sec. for each determination. In addition, the pressure gradient of an aqueous glycerol control is graphed as a function of tubular diameter at the same rate of flow. The observed data for blood is indicated by circles; that for aqueous glycerol, by squares.

A theoretical curve, based on Poiseuille's Law of Diameters, has been graphed for each sample and is represented as a solid curved line. The data for calculating this curve were taken from pressure gradients in the smallest tube.

CHART 20


Volumetric Rate of Flow
Constant at 10.4 cu.mm./sec.
□ 45% Glycerol
○ Blood
"Calculated" curve
Blood, Hct = 43.5
PRESSURE GRADIENT, mm. Hg./cm.
40
30
20
10
0.1
0.2
0.3
0.4
0.5
0.6
BORE DIAMETER (mm.)


Volumetric Rate of Flow
Constant at 10.4 cu.mm./sec.
○ Blood, Hct = 23.7
Calculated curve
Blood, Hct = 33.1
Constant flow - 10.4 cu.mm./sec.
○ Blood, Hct = 23.7
Calculated curve
Blood, Hct = 23.7
PRESSURE GRADIENT, mm. Hg./cm.
25
20
15
10
5
15
10
5
0.1
0.2
0.3
0.4
0.5
0.6
MEAN LINEAR VELOCITY (cm./sec.)

Summary of the Law of Diameters.

Blood and control fluids have been forced through hypodermic tubing whose diameter range is 0.8 mm. to 0.25 mm. The data for both constant pressure technique and constant flow technique are plotted as a function of diameter and compared with a theoretic curve calculated from Poiseuille's Law of Diameters. Both sets of data deviate by a small but consistent amount from the theoretical curve. The direction of deviation and the percentage change are identical for blood and the controls.

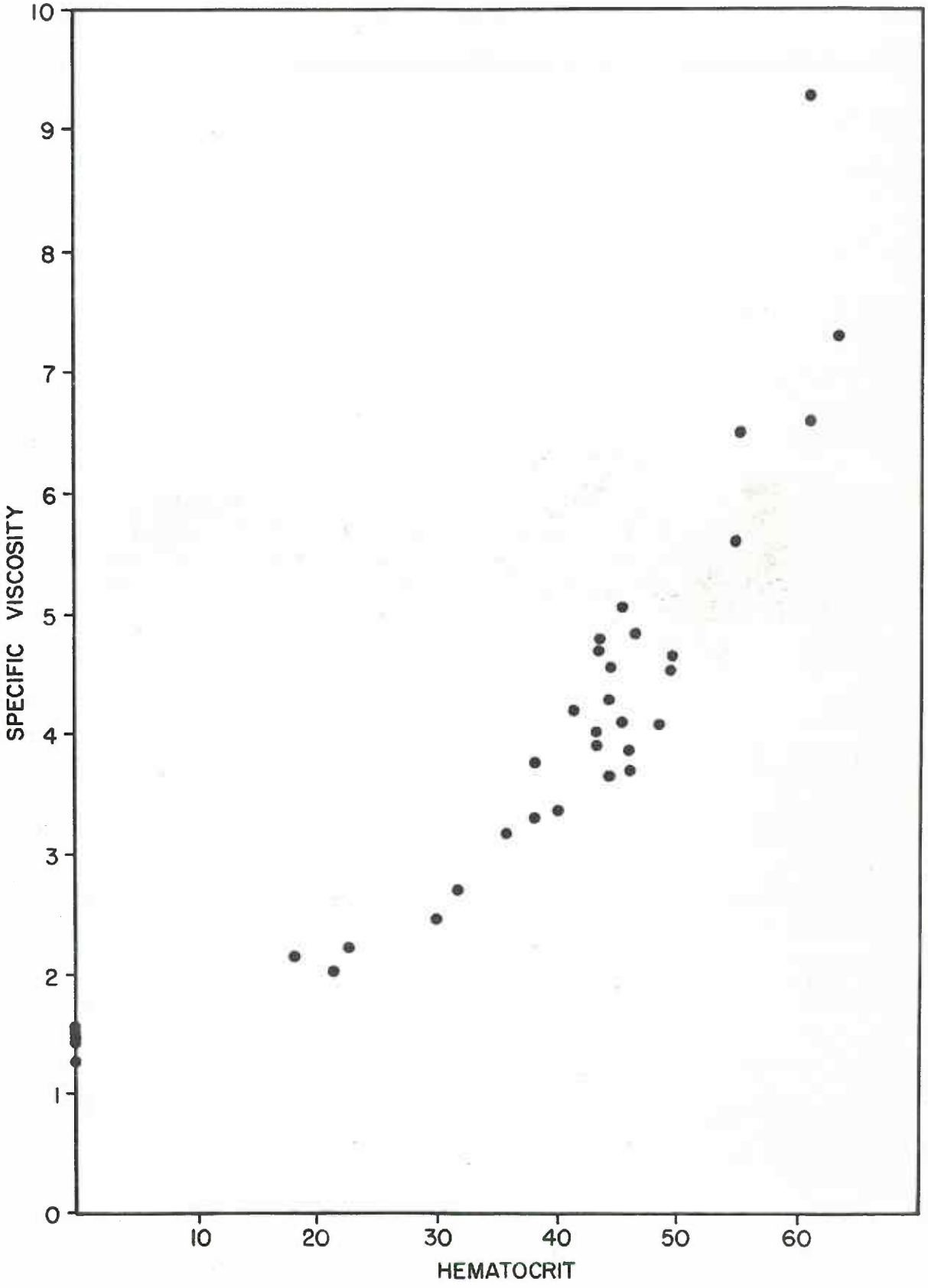
The Law of Hematocrit.

Under the conditions of our experiments, the specific viscosity of a single blood sample is a reliable physical constant, independent of the velocity of flow and the diameter of the tubing. The major factor which determines the magnitude of the specific viscosity is corpuscular concentration. Formula (8), Page 7 has been used to calculate the specific viscosity of the blood samples investigated in this work, and these are plotted in Chart 21 as a function of hematocrit.

Chart 21

The specific viscosity of the thirty blood samples and five plasma samples studied in Part I have been plotted as a function of their hematocrit. A roughly parabolic relation is observed, particularly above the normal hematocrit range of 38 - 45.

CHART 21


SPECIFIC VISCOSITY
0
1
2
3
4
5
6
7
8
9
10
10
20
30
40
50
60
HEMATOCRIT

DISCUSSION

In view of disagreement regarding the nature of blood flow in the vascular bed and in capillary tubes, it was considered that blood flow patterns in capillary tubes should be analyzed at physiologic linear velocities of flow. From such a study it should be possible to classify the blood flow in capillary tubes as either viscous or non-viscous in nature. Such a distinction would be important in any further study of hemodynamics.

In order to meet the criteria for viscous laminar flow a fluid must satisfy one requirement — its viscosity coefficient must be a constant at any given temperature. In other words, the shear stresses within the moving fluid must be directly proportional to the velocity of flow, so long as laminar flow exists. When uniform flow occurs in a horizontal cylindrical tube, the internal shear stresses cause an expenditure of energy which is evident as a decrease in the lateral head of pressure along the length of the tube. Under these conditions, therefore, the ratio of the pressure gradient to the average velocity of flow constitutes a definition of the viscosity coefficient of the fluid. It is axiomatic that a plot of the average velocity of flow as a function of the pressure gradient in such a tube be linear and have a zero intercept on the pressure axis so long as viscous laminar flow exists.

The pressure-flow data for thirty blood samples have been graphed. Without exception the plots have been linear and have intercepted the pressure axis at zero or within the experimental error of the pressure

recording system. Therefore, in each tube studied the viscosity coefficient has remained constant over a velocity range which approximates that occurring in blood vessels of similar diameter. To determine if blood behaves as a viscous fluid it is not enough to demonstrate an unchanging viscosity coefficient in each of several capillary tubes; it must also be demonstrated that the magnitude of the viscosity coefficient is not a function of tubular diameter.

The influence of tubular diameter on blood flow has been tested over a diameter range from 800 microns to 200 microns. According to Poiseuille's Law of viscous laminar flow, the volumetric rate of flow is a function of the fourth power of the diameter, providing the pressure head and viscosity coefficient remain constant. Therefore, the influence of tubular diameter on the flow of water has been compared with its influence on blood flow. The flow of each fluid is seen to be influenced in the same manner, indicating that the viscosity coefficient of blood is constant over this diameter range. In addition, the magnitude of the viscosity coefficient of normal blood has been determined in Experiments No's. 12 and 13 of Part I where flow was studied in tubes under 200 microns in diameter. The value is within the normal range in both of these experiments.

Since the viscosity coefficient of each of the blood samples studied was a reliable physical constant and was independent of linear velocity or tubular diameter, it is demonstrated that blood flow in these capillary tubes is viscous in nature. This is true even though blood is not a viscous fluid. It is an unstable suspension of

deformable cells in a colloid fluid phase; however, the dominant internal shear stresses are viscous in nature when flow occurs under the experimental conditions of this investigation. Despite the fact that blood samples have varied in hematocrit from 15% to 64%, this viscous flow pattern has been constantly observed. It may be assumed, however, that there is an upper limit to hematocrit beyond which viscous flow would not occur. In that range mutual interference of red cells and friction between red cells and the walls of the tube would undoubtedly assume an important role in contributing to the total resistance to flow. Although the present investigations of blood flow have been conducted with tubes down to 100 microns in diameter without suggesting any deviation from a viscous behavior, it may be assumed that there is a limit to tubular diameter below which a non-viscous flow pattern may predominate. However, over the diameter range and hematocrit range studied here the classic laws of viscous laminar flow apply equally well to blood flow and the flow of water.

In this study the major influence on the magnitude of the blood viscosity coefficient has been the hematocrit. This has been demonstrated in Part III where the specific viscosities of blood samples are plotted as a function of hematocrit. A roughly parabolic relation is observed. Below the normal hematocrit range, an almost linear relation exists between hematocrit and specific viscosity. Above the normal hematocrit range of 38 - 45 per cent, equal additional increments of cell volume result in an accelerated rise in specific viscosity.

The results suggest that in the peripheral vascular bed different factors are operating to control blood flow than those which can be demonstrated in capillary tubes. Heretofore, it has been common practice to apply the results obtained in investigations involving capillary tubes to flow phenomena occurring within living vessels. Fåhraeus[1] has postulated that the decrease in blood viscosity observed *in vivo* has the same basis as that which he observed in very narrow capillary tubes. Lamport[25] has utilized Rothmann's[17] data to develop a theory of the plastic nature of blood flow in capillary tubes and has applied an empirical plastic flow formula to data secured in perfused vascular beds. Both theories are thought to be erroneous on the basis of the results presented here. Additional studies are necessary before any attempt can be made to correlate the behavior of blood flow in capillary tubes with flow phenomena in the peripheral vascular bed.

SUMMARY AND CONCLUSION

Although many studies have been conducted to determine the behavior of blood flow in the vascular bed and in capillary tubes, no data are available for blood flow in narrow capillary tubes at physiologic rates of flow. In view of the anomalous nature of blood flow which is thought to exist in such tubes and the physiologic interpretations which are based on such studies, it seemed worthwhile to obtain this information.

The most informative and direct method of analyzing blood flow patterns in single rigid tubes is to plot the average velocity of flow as a function of the pressure gradient. This has been done for thirty blood samples and the plots have been compared with either a water or an aqueous glycerol control obtained in the same tube. The tubes in which flow has been studied range in diameter from 800 microns to 90 microns, and the blood samples had hematocrits which ranged from 15 to 64 per cent. In one type of experiment, volume rate of flow was controlled by a constant rate injector apparatus and the use of hypodermic syringes of different capacities. The apparatus permits a flow range from 0.1 cu.mm./sec. to 200 cu.mm./sec. The pressure head was recorded by using a Sanborn manometer coupled to a Cambridge direct writing galvanometer. In another type of experiment, pressure head was kept constant by utilizing a compressed air source; and the volumetric rate of flow was calculated by timing the flow from a calibrated reservoir. Temperature in both procedures was kept constant at 35° - 37°C. For each tube studied, a series of pressure-flow

plots was constructed for blood and for a viscous control. Without exception, the blood flow plots were linear and intercepted the pressure axis at zero or within the allowable error of the manometer system indicating a constant viscosity coefficient. Furthermore, the magnitude of the viscosity coefficient did not decrease in tubes under 300 microns in diameter.

To test Fahraeus'[1] conclusions, the hematocrit of efflux from a tube 140 microns in diameter has been determined at each of several velocities of flow. No difference was observed between the hematocrits so obtained and that of the original blood sample. Blood flow has been visualized in a glass tube 130 microns in diameter and a random dispersion of red cells throughout the fluid phase was observed.

In conclusion, blood flow in the capillary tubes studied here was viscous in nature at physiologic velocities of flow. These results suggest that the behavior of blood flow in rigid capillary tubes has been misinterpreted by previous workers and that there is no basis at the present time for explaining the aberrant alterations of viscosity *in vivo* on the basis of blood flow behavior in capillary tubes. It is considered that the work on blood viscosity in the peripheral vascular bed should be re-interpreted since it appears that mechanisms are operating which are unique to living vessels.

BIBLIOGRAPHY

1. Fåhraeus, R. and T. Lindqvist. The viscosity of blood in narrow capillary tubes. Am. J. Physiol., vol. 96, pp. 562-568, 1931.

2. Coulomb, C. A. Destinées à determiner la cohérence des fluides et les lois de leur résistance dans les mouvemens très-lents. Mem. de l'Inst. National, vol. 3, pp. 246-305, 1798.

3. Newton, I. The Mathematical Principles of Natural Philosophy, 1803, Andrew Motte translation, vol. II, section IX, p. 147.

4. Wiedemann, G. Ueber die Bewegung der Flüssigkeiten im Kreise der geschlossenen galvanischen Saule und ihre Beziehungen zur Elektrolyse. Ann. d. Phys. und Chemie, vol. 99, pp. 177-233, 1856.

5. Hagenbach, E. Ueber die Bestimmung der Zahigkeit einer Flüssigkeit durch den Ausfluss aus Röhren. Ann. d. Phys. und Chemie, vol. 109, pp. 385-426, 1860.

6. Hagen, G. Ueber die Bewegung des Wassers in engen cylindrischen Röhren. Ann. d. Phys. und Chemie, vol. 46, 423-442, 1839.

7. Poiseuille, J. L. M. Recherches expérimentales sur le mouvement des liquids de nature différente dans les tubes de très petits diamètres. Ann. de Chem. et de Physique, III series, Tome XXI, pp. 46-81, 1847.

8. Duncan, J. M. and Gamgee, A. Notes on some experiments on the rate of flow of blood and some other liquids through tubes of narrow diameters. J. Anat. & Physiol., vol. 5, pp. 150-157, 1871.

9. Ewald, G. A. Ueber die Transpiration des Blutes. Archiv. f. Anat. und Physiol., Physiol. Arbeit., vol. 82, 208-249, 1877.

10. Lewy, B. Die Reibung des Blutes. Pflug. Archiv. f. Physiol., vol. 65, pp. 447-472, 1897.

11. Hurthle, K. Ueber den Widerstand der Blutbahn. Deutsch. Med. Wochenschr., vol. 51, 809-811, 1897.

12. Nicolls, W. Haemodynamics. J. Physiol., vol. 20, 407-426, 1896.

13. Burton-Opitz, R. Ueber die Veränderung der Viscosität des Blutes unter dem Einfluss verschiedener Ernährung und experimenteller Eingriffe. Pflug. Archiv. f. Physiol., vol. 82, pp. 447-463, 1900.

Table 1

Tube A^{VI} Length = 6.775 mm. Diameter = 0.14 mm. Volume = 13340.85 cu.mm.			Tube A^{VII} Length = 1.0 mm. Diameter = 0.14 mm. Volume = 13340.85 cu.mm.		
Pressure mm. Hg 10°C.	Time sec.	Volume Flow cu.mm./sec.	Pressure mm. Hg 10°C.	Time sec.	Volume Flow cu.mm./sec.
24.753	3828.75	3.48	4.783	3926.75	3.39
50.001	1923.75	6.93	6.204	3072.00	4.34
99.343	994.00	13.42	12.129	1685.50	7.91
148.618	682.00	19.56	24.003	974.25	13.69
193.010	537.75	24.80	49.040	571.75	23.33
387.887	291.50	45.76	98.832	348.75	38.25
773.790	165.75	80.48	148.475	267.00	49.96
			193.501	224.00	59.55
			387.972	144.00	92.64
			773.717	95.00	140.43

	Volumetric Flow cu.mm./sec.							
Dial Set	Tuberculin Syringe	10 cc. Syringe #D8807	S	20 cc. Syringe #F4295	S	20 cc. Syringe #53438	S
1		2.86	0.110	5.5	0.05		
2	0.60	6.00	0.028	11.3	0.301		
3		9.31	0.095	17.5	0.105		
4		12.54	0.096	23.1	0.075		
5		15.46	0.102	28.5	0.095		
6				33.9	0.115		
7	2.37			39.7	0.161		
8				45.0	0.313		
9				51.1	0.141		
10	3.46	30.70		56.4	0.475		
15		45.00		82.0	0.358	82.0	0.33
20		59.50		109.6	0.48	109.0	0.24
25				138.5	0.38	137.0	0.94
30				164.5		166.0	0.53
35				192.3		195.0	0.38

Table 3

Table 4

Needle No.	Diameter (mm.)	Length (mm.)
Hypodermic		
18	0.84	
20	0.584	
21	0.508	
22	0.406	
24	0.3048	
25	0.254	
27	0.203	
Precision bore		
A	0.581	72.0
B	0.544	71.5
C	0.500	70.3
D	0.442	72.5
E	0.404	73.0
F	0.338	72.8
G	0.309	73.2
Drawn Capillary		
I_{ab}	0.906-0.980	11.50
III_{ab}	0.105-0.110	29.0
V_{ab}	0.140-0.162	9.4

Table 5

Sanborn Calibration

Attemuation Setting X 100			Attemuation Setting X 200		
Manometer reading mm. Hg	Calculated from galvanometer displacement mm. Hg	Per cent error	Manometer mm. Hg	Galvanometer mm. Hg	Per cent error
14	16.3	+14	24.0	24.2	+0.8
34	33.5	-1.4	54.0	48.3	-10.5
54	54		84.0	80.3	-4.5
74	72.6	-1.4	114	112.2	-1.6
* 94	94		144	143	-0.7
114	111.2	-2.5	174	176	+1.7
134	125	-9.3	204 **	204	
			234	237	+1.3
			264	263	-0.4

*
** Reference pressures

Tube No.
Diameter = 0.51 mm.
Length = 3.5 cm.
Temperature = 20°C.
Mercury manometer
Syringe No.

EXPERIMENT NO.		1			2					3				
SAMPLE NO.		I	III	VI	I	III	IV	VII	VIII	I	II	IV	VII	VIII
HEMATOCRIT =		35.7	21.3	Saline	45.9	31.6	22.7	Plasma	Water	49.4	38.0	18.2	Plasma	40% Glycerol
Dial Setting	Velocity cm./sec.	Pressure gradient mm. Hg/cm.												
10	27.3	10.1	5.7	2.8	12.9	8.9	7.5	4.6	3.3	14.3	10.4	6.6	4.3	9.8
15	41.0	16.1	10.2	4.0	20.0	14.0	11.5	7.0	4.9	23.0	-	-	-	14.9
20	54.7	20.9	12.8	5.9	26.6	19.0	15.6	9.5	6.6	-	21.5	13.4	9.5	20.2
25	68.5	27.1	17.1	7.6	33.3	24.0	19.4	12.4	8.5	36.9	-	-	-	25.5
30	82.1	32.2	20.2	9.3	39.5	28.1	23.7	15.2	10.5	45.7	32.2	20.6	14.5	30.9
35	95.9	37.9	23.9	11.9	46.2	33.4	27.8	18.1	12.3	53.8	37.2	24.3	17.8	36.4

Table 6

Tube No. 25
Diameter = 0.25 mm.
Length = 3.8 cm.
Temperature = 37°C.
Mercury manometer
Syringe No. D-8807

EXPERIMENT NO.		4				5				
SAMPLE NO.		I	II	III	IV	I	IV	VII	VIII	IX
HEMATOCRIT =		63.7	40.1	Plasma	Water	60.8	48.3	30.0	Plasma	Water
Dial Setting	Velocity cm./sec.	Pressure gradient mm. Hg/cm.								
1	10.8	18.3	8.8	3.11	2.4	15.8	10.3	6.3	3.4	2.4
3	33.0	59.0	25.5	-	8.0	50.5	32.4	18.4	11.7	7.6
5	55.7	89.5	43.5	17.8	12.9	85.3	53.2	31.6	20.0	12.5
7	78.1	121.0	60.8	-	-	113.0	73.6	44.0	28.3	17.6
10	111.8	-	87.9	37.6	25.9	-	95.3	58.4	37.2	25.3

Table 7

Tube No. 25
Diameter = 0.2540 mm.
Length = 3.8 cm.
Temperature = 37°
Sanborn Electromanometer

EXPERIMENT NO.		6		
SAMPLE NO.		I	II	III
HEMATOCRIT		41.65	40.68	Water
Dial Setting	Velocity cm./sec.	Pressure gradient mm. Hg/cm.		
2	1.18	1.4	1.5	
5	3.3	3.4	3.4	0.61
7	4.67			1.0
10	6.8	6.7	6.6	1.4
15	10.3	9.7	9.6	2.3

Table 8

Tube No. 27
Diameter = 0.2032 mm.
Length = 2.6 cm.
Temperature = 37°C.
Sanborn electromanometer

EXPERIMENT NO.		7		
SAMPLE NO.		I	II	III
HEMATOCRIT		41.65	40.68	Water
Dial Setting	Velocity cm./sec.	Pressure gradient mm. Hg/cm.		
1	0.86	3.3	1.0	
2	1.85	6.5	2.6	0.6
5	5.19	18.0	6.4	1.1
7	7.31			1.9
10	10.68		12.7	2.6
25	26.9		26.7	
35	38.0		38.4	

Table 9

Tube A Diameter = 0.581 mm. Length = 7.2 cm.		Temperature = 36°C. Syringe No. F-4295 Sanborn Electromanometer			
EXPERIMENT NO.		8			
SAMPLE NO.		I	II	III	IV
HEMATOCRIT		55		Plasma	Water
Flow Rate		Pressure gradient mm. Hg/cm.			
Dial Setting	Velocity cm./sec.				
5	10.7	2.94	1.11	0.567	0.445
10	21.3	5.81	2.22	1.08	0.89
15	31.07	8.25	3.15	1.62	-
20	41.9	11.30	-	2.17	1.8

Table 10

Tube F
Diameter = 0.338 mm.
Length = 7.28 cm.
Temperature = 35°C.
Sanborn Electromanometer
Syringe No. D-8807

EXPERIMENT NO.		9		
SAMPLE NO.		I	V	VI
HEMATOCRIT		43.	Water	Glycerol
Dial Setting	Velocity cm./sec.	Pressure gradient mm. Hg/cm.		
2	6.7	-	-	2.9
5	16.8	8.9	1.7	8.9
10	34.1	17.7	3.9	17.2
15	51.5	26.0	6.0	25.2
20	66.9	34.1	8.2	-
25	-	-	-	43.1

Table 11

Tube F
Diameter = 0.338 mm.
Length = 7.28 cm.
Temperature = 35°C.
Sanborn Electromanometer
Tuberculin Syringe

EXPERIMENT NO.		9		
SAMPLE NO.		I	II	III
HEMATOCRIT		43.2	54.8	Water
Dial Setting	Velocity cm./sec.	Pressure gradient mm. Hg/cm.		
2	0.67	0.3	0.5	-
5	1.87	0.8	1.3	0.24
7	2.64	1.1	1.7	-
10	3.86	1.5	2.4	0.48
15	5.80	2.4	3.4	0.71
25	9.7	4.1	-	-
35	11.6	5.1	-	-

Table 12

Tube I
Diameter = 0.090 - 0.0980
Length = 1.15 cm.

Temperature = 35°C.
Tuberculin Syringe
Sanborn electromanometer

EXPERIMENT NO. 20

SAMPLE NO.		I				II			
HEMATOCRIT =		40.68				Water			
Dial Setting	Volume Flow cu.mm./sec.	Pressure mm. Hg							
		P_a	P_b	P_{ab}	$\frac{P_{ab}}{cm.}$	P_a	P_b	P_{ab}	$\frac{P_{ab}}{cm.}$
10	3.5	472	217.0	*310	*270	*187	69.1	*119	*103.5
7	2.39	370.9	151.0	*218.0	*190	132.0	*48	* 83	* 72
5	1.7	262.5	106.2	*155.0	*135	95.5	34.12	* 60	* 52
2	0.62	103.0	38.8	* 62.0	* 54	36.5	13.35	* 24	* 20.9
1	0.30	54.8	*22.0	* 32.0	* 28	-	-	-	-

* Read off chart

Table 13

Tube III
Diameter = 0.105 - 0.110
Length = 2.90 cm.

Temperature = 36°C.
Tuberculin Syringe

EXPERIMENT NO. 1

SAMPLE NO.		I				II			
HEMATOCRIT		43.4				Water			
Dial Setting	Volume Flow cu.mm./sec.	Pressure mm. Hg P_a	P_b	P_{ab}	$\frac{P_{ab}}{cm.}$	P_a	P_b	P_{ab}	$\frac{P_{ab}}{cm.}$
2	0.62	193.2	92.7	*84.0	*29.0	40.5	*27	*17.0	5.87
5	1.7	485	269.5	*219	75.5	115.6	70.5	*44.0	15.2
7	2.39	-	373	-	-	160.5	*90	*63	21.7
10	3.5	-	-	-	-	240.2	144	*87	30.0

* Read off chart

Table 14

Tube V
Diameter = 0.147 mm.
Length = 0.94 cm.

Temperature = 36°C.
Tuberculin Syringe

EXPERIMENT NO. 12

SAMPLE NO.		I				II			
HEMATOCRIT		43.3				Water			
Dial Setting	Volume Flow cu.mm./sec.	Pressure mm. Hg							
		P_a	P_b	P_{ab}	$\frac{P_{ab}}{cm.}$	P_a	P_b	P_{ab}	$\frac{P_{ab}}{cm.}$
5	1.7	30.5	2.5	*26.3	28.0	7.0	-	-	-
10	3.5	59.8	4.9	*53.0	56.5	14.0	-	-	-
15	5.2	85.1	7.4	*79.5	84.6	20.9	4.4	16.5	17.6

* Read off chart

Table 15

Sample	Det'n No.	Dial Setting	Velocity cm./sec.	Hematocrit	Hemolysis
I	1 (Control)	(Control)		44.9	0
	2	5	19	44.1	+
	3	10	38	43.8	+
	4	15	57	44.3	+
	5	5	19	43.8	+++
II	1 (Control)	(Control)		45.6	0
	2	37	140 ± 5	44.8	+
	3	25	95	44.9	+
	4	15	57	45.2	+
	5	5	19	44.7	+++

Table 16

Tube E Diameter = 0.404 mm. Length = 7.30 cm.			Temperature = 35°C. Flow volume = 200 cu.mm. Water manometer			
EXPERIMENT NO.			14			
SAMPLE NO.	I		II		III	
HEMATOCRIT	44.17		45.61		Water	
Pressure gradient mm.Hg/cm.	Flow					
	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.
2.74	8.79	6.78				
2.02	6.13	4.73				
1.43	3.98	3.07				
0.716	1.19	0.92				
2.84			6.75	5.20		
2.12			4.43	3.42		
0.635			0.768	0.59		
1.24			2.36	1.82		
2.45					28.69	22.38
1.67					18.24	14.25
1.16					11.69	9.14
0.70					5.65	4.42
0.475					2.86	2.23

Table 17

Tube F
Diameter = 0.338 mm.
Length = 7.28 cm.

Temperature = 35°C.
Flow volume = 200 cu.mm.
Water manometer

EXPERIMENT NO. 15

SAMPLE NO.	I		II		III		IV	
HEMATOCRIT	38.05				45.24		Water	
Pressure gradient mm.Hg/cm.	Flow							
	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.
2.56	4.33	4.83						
1.80	2.46	2.74						
1.15	1.32	1.47						
0.85	0.723	0.806						
2.57	3.96	4.41						
2.07	3.08	3.43						
1.63	2.21	2.46						
1.14	1.38	1.54						
0.76	0.67	0.746						
0.76	0.66	0.735						
3.03			6.15	6.86				
2.29			3.98	4.44				
2.31			4.28	4.77				
1.41			2.18	2.43				
0.955			1.19	1.33				
2.94					4.28	4.77		
1.48					1.76	1.96		
0.99					1.06	1.18		
1.00					1.09	1.22		
0.63					0.53	0.59		
2.56							15.77	17.6
1.86							10.48	11.7
1.52							8.60	9.59
1.18							6.46	7.21
0.94							4.55	5.06
0.73							3.38	3.77

Table 18

Tube F Diameter = 0.338 mm. Length = 7.28 cm.		Temperature = 35°C. Flow volume = 200 cu.mm. Mercury manometer
EXPERIMENT NO.		15
SAMPLE NO.		V
HEMATOCRIT		60.6
Pressure gradient mm.Hg/cm.	Volume flow cu.mm./sec.	Velocity cm./sec.
12.90	8.34	9.30
12.90	8.38	9.34
10.2	6.91	7.70
10.1	6.62	7.38
7.96	5.31	5.92
7.96	5.55	6.19
5.08	3.55	3.96

Table 19

Tube G Diameter = 0.309 mm. Length = 7.32 cm.					Temperature = 35°C. Flow volume = 200 cu.mm. Water manometer			
EXPERIMENT NO.	16							
SAMPLE NO.	I		II		III		VI	
HEMATOCRIT	46.9		46.8		44.4		Water	
Pressure gradient mm.Hg/cm.	Flow							
	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.
2.93	2.13	2.82						
2.94	2.24	2.97						
2.06	1.35	1.79						
1.32	0.97	1.28						
0.67	0.72	0.41						
2.78			2.02	2.67				
2.82			2.29	3.03				
2.08			1.60	2.12				
2.08			1.57	2.08				
1.44			0.94	1.25				
1.44			0.96	1.27				
0.88			0.50	0.66				
0.92			0.51	0.68				
0.60			0.16	0.21				
0.65			0.17	0.23				
2.82					2.38	3.15		
2.82					2.34	3.10		
1.93					1.43	1.89		
1.94					1.45	1.92		
1.08					0.64	0.85		
1.08					0.66	0.87		
2.86							11.00	14.57
2.87							11.09	14.69
1.90							6.90	9.14
1.92							7.03	9.31
0.96							2.90	3.84
0.98							2.95	3.91
1.69							6.17	8.17
1.70							6.29	8.33
1.05							3.45	4.57
1.08							3.57	4.73
0.54							1.26	1.67

Table 20

Tube G
Diameter = 0.338 mm.
Length = 7.28

Temperature = 35°C.
Flow volume = 200 cu.mm.
Mercury manometer

EXPERIMENT NO.	17					
SAMPLE NO.	IV		V		VI	
HEMATOCRIT	42.9		49.5		Water	
Pressure gradient mm. Hg/cm.	Flow					
	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.
9.56	10.69	14.17				
9.56	10.68	14.18				
4.51	4.93	6.53				
4.51	5.05	6.69				
2.53	2.83	3.75				
2.60	2.98	3.95				
9.02			7.86	11.26		
6.79			6.24	8.98		
4.30			3.83	5.51		
4.30			3.86	5.53		
4.78					20.74	27.5
4.74					21.05	27.9
2.91					13.13	17.4
3.28					15.38	20.4
3.35					15.81	20.9

Table 21

Tube No. 25 Diameter = 0.2540 mm. Length = 3.8 cm.			Temperature = 35°C. Flow volume = 200 cu.mm. Mercury manometer	
EXPERIMENT NO.	18			
SAMPLE NO.	I		II	
HEMATOCRIT	45.8		Water	
Pressure gradient mm.Hg/cm.	Flow			
	cu.mm./sec.	cm./sec.	cu.mm./sec.	cm./sec.
26.6	15.76	31.1		
26.6	16.00	31.6		
14.4	8.86	17.5		
14.6	8.87	17.5		
7.0	4.45	8.8		
7.1	4.45	8.8		
4.2	2.42	4.8		
4.2	2.61	5.2		
14.18			31.90	62.9
14.21			32.36	63.8
8.45			17.48	34.4
8.55			17.77	35.0
3.97			9.35	18.4
4.00			9.47	18.6

Table 22

Table 23

Temperature = 35°
20 cc. Syringe F-4295
Pressure head = 17 mm. Hg = 2 mm. Hg/cm.
Sanborn electromanometer
Hypodermic tubing 18 - 25

EXPERIMENT NO.	19	
SAMPLE NO.	I	II
HEMATOCRIT =	37.0	Water
	Volumetric flow cu./mm./sec.	

Tube Diameter	Dial Set	Flow	Dial Set	Flow
0.84	27.1	150.5		
0.69	12.1	68.5	36	200
0.58	7.0	39.6	22.6	125
0.51	3.3	18.3	12.3	69.5
0.41	1.8	10.0	5.5	30.8
0.31	0.7	4.0	1.9	10.2
0.25	0.3	1.6	1.1	5.8

Table 24

Tuberculin syringe
Dial setting = 30
Volumetric Flow Rate = 10.4 cu. mm./sec.
Temperature = 35°
Hypodermic Tubing 20 - 27

EXPERIMENT NO.	20			
SAMPLE NO.	I	II	III	IV
HEMATOCRIT =	43.5	33.1	23.7	45% Glycerol
Tube Diameter	Pressure gradient mm. Hg/cm.			
0.203	41.0	22.7	17.3	40.4
0.254	17.7	10.7	7.5	20.0
0.406	6.5	3.3	2.8	4.2
0.508	1.4	0.8	0.4	1.5
0.584	0.9	0.7	0.5	0.8