STUDIES ON THE VELOCITY OF BLOOD FLOW: *II. The Velocity of Blood Flow in Normal Resting Individuals, and a Critique of the Method Used*

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J Clin Invest. 1927;4(1):15-31. https://doi.org/10.1172/JCI100110.

STUDIES ON THE VELOCITY OF BLOOD FLOW

II. The Velocity of Blood Flow in Normal Resting Individuals, and a Critique of the Method Used[1]

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(Received for publication October 4, 1926)

INTRODUCTION AND HISTORICAL RESUMÉ OF PREVIOUS MEASUREMENTS OF THE VELOCITY OF BLOOD FLOW

Since the beginning of experimental physiology the velocity of blood flow has attracted the interest of students of the circulation. Harvey (1) in 1628 stated ". . . . the circuit of the blood is accomplished now more rapidly, now more slowly according to the temperament, age, etc. of the individual, to external and internal circumstances, to naturals and non-naturals,—sleep, rest, food, exercise, affections of the mind and the like." But the first physiologist who attempted actually to measure the velocity of blood flow was Stephen Hales (2). He estimated the velocity of the blood flow in the aorta of the horse to be 1734.9 feet per hour (page 21); and in man 8952.0 feet per hour (page 47). By direct microscopic observation of the capillaries of the frog's lungs, he estimated the speed to be 0.1 of an inch in $\frac{1}{472}$ second, or about 50 inches per second. He believed the velocity of blood flow in the capillaries of the abdominal muscles to be $\frac{1}{43}$ that observed in the lung. Since then, numerous investigators have made measurements.

Eduard Hering (3) in 1829, studied the circulation time of the horse and found that it required 26.2 seconds for a particle to pass from jugular vein to jugular vein.

An extensive study was made by Karl Vierordt (4) who found that the circulation times over analogous paths in different animals bore

[1] This study was aided by a grant from the Proctor Fund of the Harvard Medical School for the Study of Chronic Diseases.

an inverse relation to their size, that is to say, the smaller the animal, the greater the velocity. He also observed that the circulation times were related to the pulse rate, in that, regardless of the size of the animal the mean circulation time of the path from the external jugular vein back to the external jugular vein corresponded to the time of twenty-six to twenty-nine heart beats. From this observation he made the inference that in man the circulation time from one external jugular vein back to an external jugular vein occupied 23.1 seconds if the heart rate were 72.

A new interest was taken in the subject when G. N. Stewart (5) began in 1894 to publish his observations on the circulation times of various pathways of the animal body. In dogs he found that from the right ventricle to the aorta, 1.7 to 8 seconds were required according to the size of the dogs used.

The only attempt to measure the circulation time in man was made by Koch (6). He injected fluorescein into the cubital vein of one arm, and observed the time of arrival of the dye in the vein of the opposite elbow. In fifty-one normal male persons between the ages of fifteen and seventy-nine, he found the average to be 20.4 seconds. We attempted to confirm Koch's results but found it difficult to obtain satisfactory measurements due to lack of coöperation on the part of the patients, to the variability of flow through the needle, and to the tendency of the blood to clot. The recognition of the first trace of fluorescence is often attended with difficulty. In spite of its drawbacks, we utilized the fluorescein method in order to confirm our results with those gained by another method.

In order to obviate the disadvantages of the previous methods, we devised and utilized a method outlined in a preceding communication. This study presents a critique of our method and the results of fifty-six measurements of the velocity of blood flow in fifty-three normal male individuals. The velocity was ascertained by measuring the time required for the active deposit of radium to flow from the cubital vein of one arm to the arterial vessels about the elbow of the other arm.

CRITIQUE OF THE METHOD

We have felt the trustworthiness of a method is proportional to the small number of underlying assumptions. We have therefore under-taken to verify by direct observation every step of our procedure, and to control as far as possible the variable factors. The chief precautions we have observed are the following.

I. Preparation of the active deposit

The active deposit is collected on a platinum needle electrode.[2] The needle is moistened with 10 per cent hydrochloric acid in a capillary tube, and concentrated sodium hydroxid is then added until the solution is neutral to phenol red. This procedure is performed in a glass capillary tube from which the fluid is drawn up into a 1 cc. tuberculin syringe, and from this injected into an arm vein. The effect of an increase in volume of the blood stream can be disregarded since the volume injected ranges from 0.1 to 0.2 cc. So minute an amount of hypertonic solution can exert no effect of physiological consequence.

II. Injection of the active deposit

The injection is performed in the following manner. A tourniquet is applied for as short a time as possible, while a sharp needle connected to a three-way stopcock is inserted into the lumen of the vein. The tourniquet is then removed. By connecting the needle to a glass manometer containing sodium citrate, the venous pressure is measured according to the method of Moritz and Tabora. The rapid descent of the citrate solution in the manometer tube, and the presence of the respiratory undulations indicate that the needle communicates freely with the vein. The stopcock is then turned and the active deposit injected. The volume is so small that only a fraction of a second is required for the injection. The duration of the injection, is a small fraction of the time which elapses between that of injection and that of arrival at the opposite arm, and constitutes therefore, a negligible error only of not more than 0.5 second. Three to five minutes elapse from the time the tourniquet is removed until the active deposit of radium is injected. Any circulatory changes caused by the application of the tourniquet are therefore reduced to a minimum.

[2] A complete description of this procedure will appear in a forthcoming communication.

III. The condition of the patient

All the patients studied were convalescent from diseases neither cardio-respiratory, nor metabolic, nor haemic in nature. Physical examination at the time of the test revealed no cardio-respiratory abnormalities. Practically all the observations were made under basal conditions, twelve to fourteen hours having elapsed since the last meal. The patient always rested in bed at least twenty minutes beforehand. By explanation and by obtaining the patient's consent and coöperation, apprehension was obviated. The temperature, the pulse rate and the rate of respiration were noted. The apparatus was always set in motion for a short period before the onset of the observation to accustom the patient to the unusual environment. The pulse was counted again immediately after the measurement, and was seldom found to have changed more than five beats. Several persons showed a persistently high ventricular rate before and after the test.

IV. Site of the active deposit of radium at the time of the onset of the ionization effect

It is, of course, of fundamental importance to be certain that the onset of the disturbance in the cloud ionization chamber is due to radium C in the vessels of that portion of the arm immediately adjacent to the celluloid collar, and not to its presence elsewhere, as it courses through the other vessels of the body. To protect the chamber, a lead block 80 to 220 mm. thick was used which absorbed the radiations which issued from the approaching radium C. According to Rutherford (7) lead of this thickness should, theoretically, more than suffice. Practically, if the equivalent of the entire amount injected was placed behind the lead block, the small amount of penetrating radiation reaching the cloud chamber was negligible. The disturbance set up in the chamber by the short secondary low velocity beta rays consists of short fuzzy tracks which are in striking contrast to the bundles of straight beta ray tracks that appear when the active deposit reaches the arterial vessels of the arm about the celluloid collar. The C. T. R. Wilson type of apparatus[3] enables one, moreover, to judge the direction of the tracks, and so to gain an idea of its source.

[3] The apparatus is described in a preceding communication.

A demonstration even more conclusive of the fact that the cloud effect was due to active deposit in the vessels of the arm was obtained in every experiment by directing the patient to withdraw his arm from the chamber and to place it behind the lead shield immediately upon the conclusion of the velocity measurement. At this moment the body was still giving out radiation. The striking disappearance of the straight beta ray tracks showed that the cloud effect had not been due to radium C present in the chest or in the rest of the body.

V. Localization of the source of the cloud effect in the blood vessels of the arm

The above facts establish that the cloud effect is due to active deposit in the vessels of the arm placed about the detecting chamber. One might still question, however, whether at the time of the appearance of the cloud, the active deposit was in the arteries, in the capillaries, or in the veins. Inability to answer this question would not necessarily invalidate the use of the method as a means of securing measurements for purely comparative purposes. The significance of the method would, however, be greatly heightened if one could establish the site of the active deposit at the time of the onset of the disturbance in the ionization chamber. From the point of view of theoretical physics, it is almost certain that the onset of the cloud effect is due to the entry of the blood containing active deposit into the larger arteries about the elbow. The cloud chamber records the path traversed by a single electron, so that a few atoms of active deposit should be sufficient to produce the cloud effect.

To secure direct evidence upon this question, the following procedures were carried out. The arm-to-arm velocities of a group of patients were ascertained according to the usual procedure. The values obtained are shown in table 1, column 5. Subsequent measurements were also made on these patients by injecting 2 cc. of a 1.5 per cent solution of fluorescein to which had been added 2 to 4 millicuries of the active deposit. We have already described the limitations in the use of fluorescein, but it affords nevertheless the only available means of verifying certain aspects of our method. The solution was injected into the cubital vein of the right arm, while a large needle was inserted into the cubital vein of the other arm.

Samples of blood were collected every three or five seconds. Each sample of blood was tested for the presence of active deposit and for the presence of fluorescein. The observations were made independently by different observers. The presence or absence of the substances was ascertained separately and checked without knowledge of the sequence in which the blood had been collected. The first specimen of blood in which the dye or active deposit was detected, is named and recorded according to the length of time after the intravenous injection of the solution. The time of the injection is

TABLE 1

Comparison of the circulation times obtained by the radium active deposit method, and by testing the venous blood directly for the presence of fluorescein and for the presence of radium active deposit

Number of measurement	Name	Age	Diagnosis	Circulation time		
				Radium-active deposit method	Fluorescein test	Direct radium-active deposit test
				seconds	*seconds*	*seconds*
34	S. F.	19	Normal	15	25–30	
36	T. G.	78	Myocardial degeneration	48	60–65	
37	P. S.	37	Malignant	25	30–35	
49	R. M.	66	Myocardial degeneration	26	35–40	
58	T. M.	64	Arterio sclerosis	29	45	45
69	D. M.	53	Auricular fibrillation	42	45–50	45–50
71	T. M.	53	Auricular fibrillation	25	30–35	30–35

regarded as zero, this assumption introducing an error of not more than two seconds.

Certain of the results are significant. First, the cloud effect, according to the usual procedure, took place in every instance at least five seconds earlier than the appearance of fluorescein or active deposit in the blood drawn from the antecubital vein. This signifies that the appearance time of the active deposit of radium as noted by the emergent rays from the tissues of the arm is always observed at least some five seconds before it reaches the corresponding vein of that arm. The presence of radium C or fluorescein in a twenty-five to thirty second sample may, of course be due to the arrival of these substances during the first, or during the last second of the collection so that these results cannot be interpreted too precisely. The fact that there was at least a five-second difference is of considerable importance, however. The time for blood to course from the arterial to the venous side of the arm is probably not more than five seconds. We therefore believe these findings to be further evidence that the onset of the cloud effect is due to radiation from active deposit in the arterial vessels of the arm. It might be argued that the amount of active deposit in the several cubic centimeters of blood that had been withdrawn is greater than might be expected in a strip of artery 2 or 4 cm. long. To test this point, we examined a few drops of blood of each sample to learn whether the cloud effect could be observed from such small amounts.

TABLE 2

Comparison between the circulation times of the same persons obtained by the radium active deposit method and by testing the blood from the brachial artery for the presence of fluorescein

Name	Date	Circulation time		
		Radium method	Arterial puncture	Difference
		seconds	*seconds*	*seconds*
B. S.	4–9	16	12	4
A. D.	4–10	12	10	2
G. L.	4–10	18	15	3
F. D.	4–10	19	13	3

Even when only two or three drops of blood were placed on a piece of gauze and held close to the cloud chamber, the ionization effect was unmistakably present. The presence of fluorescein was not evident in such small amounts.

That radium C can yield so great an effect when present in such small amounts lends further probability to the belief that the onset of the cloud effect is due to the presence of radium active deposit in the larger arteries rather than in the smaller vessels. To gain conclusive evidence that the onset of the effect is due to the presence of active deposit in the artery, blood was withdrawn from the arteries of a few individuals. The time of arrival of the active deposit in the arterial blood averaged three seconds earlier than the times recorded in the routine measurements in the same individuals. (Table 2.) The meaning of these differences is difficult to interpret, since the arm-to-arm circulation times may vary three seconds in the same person. Since the circulation times by arterial punctures are in general shorter than the routine determinations, two possibilities may be offered: (*a*) the actual time of onset of the ionization effect may not appear until the active deposit enters the smaller arteries, or (*b*) the arterial puncture times may give an earlier result because of the change in the experimental conditions. The gradient of pressure within the needle falls from the arterial blood pressure at one end to atmospheric pressure at the other. Gradients such as this do not exist normally in the body. The flow may be more rapid, therefore, through the needle than it would be with the circulation of the arm undisturbed.

The substitution of the normal peripheral resistance by zero pressure at the collecting end of the needle is analogous to the condition existing in arteriovenous aneurysm. It is interesting to note that Lewis and Drury (8) found in man that "the quantity of blood leaking from a large limb artery to the corresponding vein in cases of arteriovenous aneurysm may be very considerable, amounting to a fifth or even a half of the quantity thrown out by the left ventricle at each beat." It is plausible, therefore, that the flow from the artery through a needle open to atmospheric pressure may be more rapid than that normally present, and might account for the shorter times observed.

VI. Variation of dosage

In order to be certain that the results were in no degree influenced by the amounts of active deposit injected, duplicate measurements were made in the same individuals, using greatly varying doses. By the time the active deposit injected into the right arm reaches the left, the concentration is diminished due to mixing of the active deposit with the blood. It is clear that if the first appearance of radium active deposit were in concentrations below that which could be detected by the ionization chamber, the onset would not be recorded until the aftercoming more concentrated solution of active deposit reached the arteries. Such an error would exhibit itself by the recording of shorter velocity times when larger doses were used. It is interesting to observe therefore that increase in the number of millicuries injected did not significantly alter the results obtained in a given individual.

VII. Repeated measurements in the same individuals

Results of any procedure such as the one presented in this paper may reflect variations inherent in the method as well as variations in the phenomenon under investigation. The preceding discussion has dealt with the precautions observed in our attempt to reduce to a minimum all variations due to the experimental procedure. Under conditions as similar as possible, and observing all the precautions that have been mentioned, we have made successive measurements of the velocity of blood flow in certain individuals. (Table 3.) The trustworthiness of the method is verified by the close correspondence of the results. As can be seen from the table, observations on certain persons were repeated on the same day while in others they were repeated on successive days. According to our experience the minimal time within which the tests can be repeated is three hours. Within this period the active deposit of radium decays spontaneously to 3 per cent of its initial value. Direct tests on the urine show that the active deposit appears within a few minutes following its intravenous

TABLE 3

Repeated determinations of the circulation time in the same persons by the radium active deposit method

Name	Age	Diagnosis	Date	Circulation time	Date	Circulation time
				seconds		*seconds*
S. T.	27	Arthritis	8–29	18	9–1	21
I. T.	53	Auricular fibrillation	8–29	63	9–1	71
F. M.	43	Auricular fibrillation	8–28	55	9–1	53
L. C.	44	Arteriosclerosis	12–2	28	12–4	27
					12–5	26
T. W.	43	Auricular fibrillation	12–16	57	12–29	47
L. B.	41	Bronchial asthma	1–5	22	1–5	22
D. S.	63	Gastro-enteritis (?)	1–5	28	1–5	26
F. B.	25	Bronchitis	1–6	18	1–6	18
G. W.	65	Polycythemia	1–11	31	1–12	34
L. P.	41	Normal	1–11	19	1–12	20
T. D.	53	Emphysema	3–15	21	4–10	19
L.	52	Tuberculosis (?)	6–18	19	6–21	23
A. D.	72	Normal	6–16	24	6–21	23
S. S.	18	Normal	6–22	18	6–22	23

TABLE 4

Measurement of the circulation times of normal male individuals and the relation to other cardio-respiratory measurements

Number of measurement	Name	Age	Surface area	Respiration	Pulse	Circulation time	Circulation time per square meter	Vital capacity	Vital capacity per square meter	Arterial pressure		Venous pressure H_2O*	Red blood cell count	Hemoglobin	Millicuries injected
										Systolic	Diastolic				
			square meter			*seconds*	*seconds*	*cc.*	*cc.*	*mm.*	*mm.*	*cm.*	*millions*	*per cent*	
179	A. D.	15	1.61	18	102	12	7			130	70	1.5			2.6
62	W. F.	22	1.82	17	86	15	8	4,600	2,530	108	70	2.1	4.76	104	1.5
26	R. B.	13	1.40	24	84	11	8	3,000	2,140	112	54	3.0	5.18	105	1.3
172	H. G.	19	1.88	19	100	15	8	4,800	2,550	128	54	4.5	5.24	102	2.2
186	F. N.	56	1.70		106	14	8								2.6
64	G. H.	47	1.93	19	70	18	9			108	62	1.0	4.36	88	1.6
66	G. L.	50	2.07	19	82	19	9	3,950	1,900	114	72	1.0	3.90	80	1.4
84	B. S.	48	1.84	15	73	16	9	4,550	2,460	121	66	2.5		95	3.2
88	F. E.	20	1.63	19	98	15	9	4,150	2,540	128	68	1.4		110	1.1
99	F. L.	39	1.88	23	81	16	9	3,800	2,050	124	46	4.5	1.05		2.6
101	R. I.	27	1.67	15	59	15	9	4,300	2,570	104	54	1.5		96	2.2
34	S. F.	19	1.64	20	71	15	9	3,800	2,310	120	55	1.5	5.10	115	9.1
207	D. F.	26	2.03	18	78	19	9								3.6
65	E. D.	35	1.71	17	71	17	10	4,100	2,390	122	66	0.5			3.4
86	F.	29	1.67	16	66	16	10	4,250	2,540	80	40	3.4	5.64	105	
102	A.	40	1.70	17	60	17	10	3,890	2,290	92	54	4.5	4.82	95	1.7
25	M. S.	23	1.56	21	72	15	10	4,200	2,690	100	40	3.5	4.13	95	1.1
42	F. B.	25	1.77	16	57	18	10	3,500	1,920	92	40	1.8	4.50	85	5.1
43	F. B.	25	1.77	18	56	18	10	3,500	1,920	94	44	1.8	4.50	85	3.9
45	A. J.	35	1.79	23	86	17	10	4,500	2,510	114	48	4.0	4.40	85	0.8
163	I. C.	15	1.48	16	61	15	10	3,150	2,250	104	68	−1.5			2.5
170	A. H.	17	1.57	17	64	16	10	3,200	2,040	118	68	2.5			2.1
173	T. C.	37	1.74	19	56	17	10	4,750	2,730	118	50	2.5			2.1

177	B. S.	67	1.60	17	102	16	10	4,250	2,650	136	66	2.8			2.9
181	G. L.	48	1.80	18	78	18	10			120	76				2.9
189	C. I.	22	1.72		86	18	11	4,300	2,520	124	74	3.5			2.5
190	C. W.	58	1.85		82	20	11	4,550	2,510	135	80	2.5			3.1
201	A. D.	72	2.28	16	64	24	11			120	64	−3.5			3.1
28	A. L.	31	1.67	23	72	21	12	3,100	1,860	104	54	3.4	4.86	102	1.6
32	R.	18	1.64	17	61	20	12	4,300	2,610	116	80	0.5	5.70	100	1.1
35	A. M.	26	1.61	18	62	20	12	3,950	2,450	130	64	1.2	6.23	108	6.7
51	S. W.	27	1.87	21	82	22	12	5,400	2,880	114	72	2.5	6.20	104	4.5
55	L. P.	41	1.78	19	67	20	12	4,900	2,750	110	68	0.0	5.24	108	3.7
67	H. T.	65	1.56	26	112	19	12	3,100	2,000	130	68	1.0	4.04	85	4.6
72	M.G.	62	1.65	20	84	20	12	4,000	2,420	170	68	2.5	5.04	95	1.6
83	J. F.	44	1.53	18	70	18	12	4,000	2,610	134	72	1.4	4.42	96	1.7
47	J. G.	37	1.67	21	64	21	13	3,400	2,040	102	42	1.0	4.20	90	6.0
77	R. R.	40	1.59	16	57	21	13	4,150	2,670	112	54	1.2	5.12	95	2.5
220	S. S.	18	1.75		70	23	13			110	74				4.6
94	D. V.	39	1.46	19	65	20	14	3,850	2,630	114	56		5.20	85	2.0
211	A. D.	73	2.28		74	23	10								4.3
212	T. A.	45	1.65		89	16	10	3,900	2,360	108	58	5.0			4.2
217	S. S.	18	1.75		78	18	10	3,750	2,140	108	70	2.0			4.2
22	A. L.	45	1.98	20	90	21	11	3,800	1,910	130	76	3.0	4.96	85	1.5
27	R. T.	45	1.98	21	80	21	11	3,900	2,000	90	54	3.0	4.96	85	5.5
46	G. B.	25	1.58	22	82	18	11	3,000	1,890	104	40	2.0	4.60	85	4.0
54	L. P.	41	1.78	19	77	19	11	4,900	2,750	108	66	3.0	4.96	94	5.2
81	T. E.	43	1.81	19	64	19	11	4,350	2,400	130	68	1.2	3.96	75	1.4
92	K. H.	36	1.67	17	70	19	11	4,850	2,900	94	54	3.0	4.20	68	2.5
93	A. C.	60	1.73	19	76	19	11	3,850	2,230	112	68	1.0	4.04	84	1.7
103	A. J.	51	2.00	12	82	22	11			152	100	2.5		70	1.2
166	A. B.	25	1.71	16	61	18	11	4,550	2,660	120	84	3.5		105	2.5
184	W.M.	69	1.69		92	18	11								2.9

* To correspond to the level of the right auricle, 5.0 cm. should be added to these measurements.

injection. Less than the theoretical 3 per cent is present within the body at the end of three hours.

VIII. Single measurements in normal individuals

The fundamental functions of a system as complex as the circulation are many. Isolated measurements of a single aspect are difficult to interpret. To gain as much insight as possible into the significance of velocity measurements, we therefore observed as many related phenomena as possible (table 4). The age, the height, and the weight were recorded. The blood pressure, the respiratory rate, the mouth temperature, and the ventricular rate were noted just before the velocity of blood flow was determined. The ventricular rate was counted again immediately after each measurement and never varied more than ten beats from its previous rate. The venous pressure was measured immediately before the active deposit of radium was injected. The vital capacity of the lungs was ascertained and the blood was examined on the day the velocity of blood flow determination was made. The hemoglobin was measured by the Tallquist method. The results of our observations are tabulated below.

DISCUSSION

For the purpose of establishing a critique of the method it was necessary to measure the velocity of blood flow in patients who exhibited various lesions of the circulatory system. The following discussion refers, however, solely to the data derived from the study of normal male individuals (table 4). All the subjects were males, convalescent from diseases neither metabolic nor cardio-respiratory, nor haemic in origin. The related data recorded in the tables, the careful histories and physical examinations at the time of the test establish the normality of these individuals. Most of them were about to be discharged from the surgical services. They may be regarded as satisfactory controls. These patients might not be considered as strictly normal because of their stay in the hospital; nevertheless we believe they serve as a more accurate basis of comparison to patients similarly hospitalized, who exhibited pathological lesions of the circulatory system. Moreover, hospitalization probably exerts no significant effect on the velocity of blood flow since some individuals who were not hospitalized showed times essentially similar to the "normal" hospitalized men.

Relation of age to the velocity of blood flow

The basal metabolic rate tends to become lower with advancing age and it is therefore of interest to learn whether the velocity of blood flow undergoes an analogous change. There is apparently in normal individuals no critical age beyond which the velocity of blood flow becomes slower. (Table 5.) The velocity of blood flow in a normal adult individual, therefore reflects the actual condition of the circulation, independent of age. The circulation times of children between the ages of twelve and fifteen, obtained in a few determinations appear to be shorter both in absolute values and in values reduced to square meter of body surface.

TABLE 5

The relation of the average circulation times of normal male persons to the age, the surface area and to the vital capacity

Age	Number of cases	Circulation time	Variations	Circulation time per square meter	Variations	Vital capacity	Vital capacity per square meter
		seconds	*seconds*	*seconds*	*seconds*	*cc.*	*cc.*
15–29	22	17	12–23	10	7–13	4,000	2,390
30–39	8	19	16–21	11	8–14	4,170	2,430
40–49	12	19	16–21	11	9–13	4,070	2,370
50–75	12	19	14–24	11	8–14	3,720	2,160

Relation of blood pressure to the velocity of blood flow

Other factors remaining constant, the velocity of blood flow between any two points is proportional to the difference in pressure between these two points, and is inversely proportional to the resistance. Were all the factors of the circulation to remain constant, we might expect that when the venous pressure is zero, the higher the mean arterial pressure, the greater would be the velocity of blood flow. It is of interest to learn, therefore, whether an increase in blood pressure tends to be associated with an increase in the velocity of blood flow. The systolic blood pressures in these individuals ranged from 80 to

136 mm., and the diastolic from 41 to 66. In two persons, however, the measurements were 170 and 152 mm. systolic, and 68 and 100 mm. diastolic, respectively, although in them no disease of the circulation was discovered either on physical examination or by the usual tests. The increase in blood pressure may have been due to excitement at the time of the measurement of velocity of blood flow. Examination of our data reveals no evident relation between physiological variation in blood pressure and physiological variation in circulation time. In normal individuals increased blood pressure is probably associated, therefore, with proportionate increase in peripheral resistance. Further description of the dynamics of the arterial blood pressure and its relationship to the velocity of blood flow will be reserved for a later communication in which the results in subjects with hypertension will be discussed.

Relation of the ventricular rate to the velocity of blood flow

Although the ventricular rates of these subjects varied from 56 to 112, there was no corresponding alteration in the velocity of blood flow. This is not surprising inasmuch as the velocity of blood flow is more closely related to the minute volume output, which in turn is a product of the stroke volume times the ventricular rate. It is interesting to note that the minute volume output does not necessarily bear a direct relationship to the ventricular rate. E. K. Marshall (9) using the direct Fick method in trained unanesthetized dogs, found in four dogs that the ventricular rate may vary from 50 to 250 without change in the minute volume output. In a pregnant dog there was, however, an increased output with an increase in the pulse rate.

In twenty-one[4] normal individuals of various ages the ventricular rate at the time of the test was higher than eighty, the average being ninety. The average circulation time of these individuals was seventeen seconds, the average circulation time per square meter of body surface was ten seconds. In five[5] normal individuals in whom the ventricular rate averaged one hundred and four, the average circulation time was fifteen seconds and the average circulation time per

[4] These are patients number 22, 26, 45, 46, 51, 62, 66, 67, 72, 88, 99, 103, 177, 179, 184, 186, 189, 190, 195, 212, 127, table 4.

[5] These are patients number 67, 177, 179, 186, 172, table 4.

square meter of body surface was nine seconds. The findings indicate, therefore, that in normal resting individuals with a rather considerable increase in ventricular rate there tends to be only a slight increase in the velocity of blood flow.

On the other hand in five normal[6] persons whose ventricular rate was less than sixty at the time of the test (average fifty-seven), the average circulation time was eighteen seconds; or ten seconds per square meter. The finding therefore indicates that in these individuals the slow ventricular rate was not associated with an appreciable slowing of the blood flow. The relation of abnormal ventricular rates and rhythms to the velocity of blood flow will be discussed in a subsequent communication.

Relation of surface area to the velocity of blood flow

It has long been known that both the heat production in man and the vital capacity bear a definite relationship to the surface area. The average circulation time of individuals between the ages of fifteen and twenty-nine was seventeen seconds, and when reduced to surface area was ten seconds. In the persons between the ages of thirty and seventy-five the average circulation time was found to be nineteen seconds, or, in terms of surface area, eleven seconds per square meter. The deviation from the mean remained proportionately about the same whether the actual circulation time was taken or whether the time was referred to the surface area.

Significance of the variations in velocity of blood flow in normal individuals

Successive velocity measurements in a given normal individual have not varied by more than three seconds except in two instances; the extreme range from one individual to another has amounted to ten seconds. The cause of this variation, can, in all probability not be assigned to a single factor. Vasomotor instability, peripheral resistance, character of the vessel walls, length of the path traversed, cross-sectional area of the vessels, force of cardiac systole, minute volume output—all these play important rôles in controlling the velocity of

[6] These were patients number 42, 43, 77, 101, 173, tables 4.

blood flow. It is manifestly impossible to venture an opinion on the basis of the now available facts as to the relative importance of these conditions in causing the variation which we have observed.

CONCLUSIONS

1. The chief precautions observed in estimating the velocity of blood flow by the radium active deposit method are described.
2. Direct and indirect evidence is presented that the ionization effect is due to the radiation which emerges from the arterial blood of the arm.
3. Considerable variations of the dose of the active deposit of radium do not influence the results obtained.
4. Repeated measurements in eleven individuals with regular rhythm agreed within an average of two seconds. The variation never was more than three seconds except in two individuals in whom it amounted to four seconds and five seconds, respectively.
5. Measurements can be repeated as early as three hours.
6. The circulation times of fifty-three normal resting male individuals are presented.
7. The arm to arm circulation time in normal resting individuals may vary between fourteen and twenty-four seconds when the active deposit is injected into the cubital vein of one arm and the onset of radiation from the arterial vessels of the other arm is detected.
8. The arm to arm circulation time does not become more prolonged with advancing age as measured by the method described. There is no critical age beyond which the velocity of blood flow tends to diminish.
9. The average arm to arm circulation time in fifty-three normal persons between the ages of fifteen and seventy-five was eighteen seconds.
10. The average arm to arm circulation time when reduced to square meter of body surface was ten seconds in individuals between the ages of fifteen and twenty-nine, and eleven seconds between the ages of thirty and seventy-five.
11. A few measurements in children indicate that the velocity of the blood flow is somewhat rapid in childhood.

12. With a conspicuous increase in the pulse rate there is a slight but definite tendency toward an increased velocity of blood flow.

13. A relatively low ventricular rate does not seem to lower the velocity of blood flow below that exhibited by individuals with higher ventricular rates.

14. Normal variations in the blood pressure bear no relation to the normal variations in the velocity of blood flow.

We wish to express our appreciation to Dr. Francis W. Peabody for his constant advice and encouragement.

BIBLIOGRAPHY

1. Harvey, William, An Anatomical Dissertation upon the Movement of the Heart and Blood in Animals, being a Statement of the Discovery of the Circulation of the Blood. 1628. Facsimile Edition. G. Moreton, Canterbury, 1894.
2. Hales, Stephen, Statical Essays, Vol. 2. London 1733.
3. Hering, Eduard, Quoted by Tigerstedt, Robert. Physiologie des Kreislaufes Berlin u. Leipzig, 1923, Vol. 4, 58.
4. Vierordt, Karl, Die Erscheinungen und Gesetze der Stromgeschwindigkeiten des Blutes. Frankfurt A. M. 1858.
5. Stewart, G. N., Am. Jour. Physiol., 1921, lviii, 20. The Pulmonary Circulation Time, the Quantity of Blood in the Lungs, and the Output of the Heart.
6. Koch, Eberhard, Deutsch. Arch. f. Klin. Med., 1922, cxl, 39. Die Stromgeschwindigkeit des Blutes.
7. Rutherford, Ernest, Radioactive Substances and Their Radiations. London, 1913, 260.
8. Lewis, Thomas, and Drury, A. N., Heart, 1923, x, 301. Observations Relating to Arterio-Venous Aneurysm. Part 1. Circulatory Manifestations in Clinical Cases with Particular Reference to the Arterial Phenomena of Aortic Regurgitation.
9. Marshall, E. K., Proceed. of the Am. Physiol. Soc., Am. Jour. Phys., 1926, lxxvi, 178. Studies on the Cardiac Output of the Dog.