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CLINICAL STUDIES ON THE VELOCITY OF BLOOD FLOW

XI. The Pulmonary Circulation Time, the Minute Volume Blood Flow through the Lungs, and the Quantity of Blood in the Lungs[1]

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Measurement of the pulmonary circulation time in man makes possible comparison, in the same person, of the time consumed by the blood flow with the volume of blood which flows through the lungs per minute. Simultaneous measurement of these fundamental features of the circulation is of considerable interest for if the normal variations in the time of blood flow correspond to similar variations in the volume flow, the significance of each measurement would be greatly heightened. Measurement of both the volume and the time of blood flow through the lungs also affords additional evidence concerning the significance of the pulmonary circulation time. The pulmonary circulation time refers to the time necessary for a given particle of blood to appear in the left auricle after its previous entrance into the pulmonary artery. This time may be measured by the interval necessary for the fastest particle of a foreign substance to traverse the shortest available path. According to Tigerstedt (1) and von Kries (2) the speed of the central or axial portions of a stream may be twice that of the peripheral portions. Were this true, the pulmonary circulation time would be not much more than half the average circulation time of the lungs. The work of G. N. Stewart (3) as well as some observations discussed in previous communications (4) (5) indicate that the pulmonary circulation time is an index of

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the mean pulmonary blood velocity.[2] According to the formula of G. N. Stewart (3), Q equals $\frac{V.T}{60}$ where Q is the quantity of blood in the lungs; V is the minute volume flow of blood through the lungs; and T, the *mean* pulmonary blood velocity in seconds. If two of the factors are known, the third can be calculated. Were von Kries and Tigerstedt correct in their contention that the speed of the fastest particle as expressed by the "circulation time" is twice the mean velocity, substitution of the pulmonary circulation time for T, the mean velocity time, would result in magnifying Q, the quantity of blood in the lungs, which would then become twice too great. If on the contrary, the pulmonary circulation time is an index of the mean velocity, the substitution should give a result which conforms to the results of animal experiments.

Methods and Results

The crude pulmonary circulation time was measured according to the method previously described (5). The actual pulmonary circulation time, that is to say, the time interval between the arrival of the active deposit of radium in the pulmonary artery and its arrival in the left auricle was estimated by subtracting four seconds from the crude pulmonary circulation time. Four seconds includes the time the active deposit consumes in passing through the heart and varies according to the phase of the cardiac cycle at which the active deposit enters this organ. The four seconds also accounts for the time necessary for the active deposit to travel from the left ventricle to the antecubital arteries.

The minute volume of pulmonary blood flow was measured by the gasometric method of Field, Bock, Gildea and Lathrop (6). Except in the first few subjects, six to nine "alveolar" and "virtual venous" gas samples were analyzed. Occasional discrepant results due to evident errors of technique were discarded. The respiratory minute volume was measured in all subjects, and in nine of the seventeen subjects, the respiratory quotient, and the total CO_2 elimination per minute were measured after, as well as before, the collection of the

[2] By this phrase is meant "the mean time occupied by the passage of blood through the lungs."

gas samples. No gas samples were taken until the subject had reached a constant level of ventilation for, as pointed out by Field, Bock, Gildea and Lathrop (6), a marked change in ventilation immediately preceding the collection of air samples causes an incorrect value for the difference between the arterial and venous CO_2 tensions. The ventilation per minute in some subjects, as numbers 1 and 4, was somewhat high but no samples were collected until a constant state had been reached. Both the volume of the blood which flows through the lungs and the pulmonary circulation time were measured on the same day and in some persons the pulmonary circulation time was observed before and after the minute volume measurements.

The total blood volume of the subject was calculated as one-thirteenth of the body weight.

Seventeen young normal intelligent male subjects were studied. They had been properly trained in the necessary respiratory procedures. All subjects were in the post absorptive state.

The results of our studies are presented in table 1.

DISCUSSION

The average volume of blood which flows through the lungs per minute was 7.6 liters. The average actual pulmonary circulation time was 8 seconds, the average amount of blood in the lungs was 984 cc., or 21 per cent of the total blood volume. The results indicate no evident correlation in a given person between normal variations in the pulmonary circulation time (table 1, column 16) and normal variations in the volume of blood which flows through the lungs per minute. (Table 1 Column 14). It should be emphasized also that the quantity of blood in the lungs estimated by means of the pulmonary circulation time and pulmonary minute volume flow is only approximate. The minute volume method used, although probably the most trustworthy available, contains certain sources of error which preclude too precise interpretation of the results. Similarly, the estimated actual pulmonary circulation time with its correction of four seconds is in all probability approximate and not a mathematically precise expression of the mean time consumed by the blood in its pulmonary passage. The measurement of the pulmonary circulation time, and the minute volume flow were, moreover, made consecutively, whereas

TABLE 1

Measurement of the pulmonary blood velocity, the minute volume blood flow through the lungs, and the quantity of blood in the lungs

Number	Date	Age	Vital capacity	Vital capacity per square meter	Respiratory minute volume	Respiratory quotient	Alveolar CO_2 tension	Average alveolar CO_2 tension	"Virtual" venous CO_2 tension	Average "virtual" CO_2 tension	Difference arterial and venous CO_2 content	CO_2 elimination per minute	Circulation rate	Arm to heart circulation time	Crude pulmonary circulation time	Actual pulmonary circulation time	Amount blood in lungs	Weight of patient	Calculated blood volume	Total blood in lungs
	1927		*cc.*	*cc.*	*liters*		*volumes per cent*	*volumes per cent*	*volumes per cent*	*volumes per cent*	*volumes per cent*	*cc.*	*liters per minute*	*seconds*	*seconds*	*seconds*	*cc.*	*kgm.*	*cc.*	*per cent*
1	February 2	17	4,300	2,690	10.5		6.06	6.05	6.87	7.02	2.60	220	8.5	5.5	9	5	750	51.0	3,920	19
							5.76		7.03											
							6.11		7.16											
							6.11													
							6.20													
2a	February 4	36	3,250	1,957	8.3		5.91	5.94	6.77	6.99	2.82	208	7.4	13	12	8	920	58.0	4,460	21
							5.89		6.90											
							5.96		7.08											
							5.98		7.20											
2b	February 5	36	3,250	1,957	8.6		5.78	5.72	6.91	6.88	3.16	205	6.5							
							5.76		6.88											
							5.73		7.18											
							5.62													

3	February 14	21	5,050	2,729	9.4		6.06 5.88 6.15 5.79 6.16 6.00 6.22 6.32	6.08	6.34 6.53 6.38 6.68 6.46 6.87	6.54	1.49	208	13.8	4	12	8	1,850	67.3	5,200	35
4	February 15	29	4,500	2,648	11.7		5.98 6.10 6.14 5.16 6.67 6.00 6.58 6.07	6.09	6.64 6.85 7.24 6.87 7.26 6.45 6.78 7.12	6.90	2.07	184	8.8	10.5	11.5	7.5	664	58.6	4,520	15
5	February 16	25	5,000	2,719	10.3		5.30 5.24 5.41 5.35 5.49 5.31 5.37	5.35	5.98 6.32 6.47 6.41 6.57 6.74 6.03 6.27 6.45	6.36	2.63	236	8.3	6.5	11.5	7.5	1,035	67.1	5,165	20
6	February 18	23	4,400	2,525	6.7		5.65 5.68 5.56 5.56 5.71 5.58 5.63	5.62	6.55 6.61 6.59 6.48 6.74 6.57 6.80 6.79	6.64	2.82	222	7.9	10	9	5	659	61.5	4,730	14

TABLE 1—*Continued*

Number	Date	Age	Vital capacity	Vital capacity per square meter	Respiratory minute volume	Respiratory quotient	Alveolar CO_2 tension	Average alveolar CO_2 tension	"Virtual" venous CO_2 tension	Average "virtual" CO_2 tension	Difference arterial and venous CO_2 content	CO_2 elimination per minute	Circulation rate	Arm to heart circulation time	Crude pulmonary circulation time	Actual pulmonary circulation time	Amount blood in lungs	Weight of patient	Calculated blood volume	Total blood in lungs
	1927		*cc.*	*cc.*	*liters*		*volumes per cent*	*volumes per cent*	*volumes per cent*	*volumes per cent*	*volumes per cent*	*cc.*	*liters per minute*	*seconds*	*seconds*	*seconds*	*cc.*	*kgm.*	*cc.*	*per cent*
7	February 23	21	4,900	2,662	8.9		5.72	5.63	6.54	6.64	2.76	308	11.1	8	12.5	8.5	1,558	68.9	5,300	29
							5.41		6.68											
							5.67		6.91											
							5.76		6.46											
							5.69		6.88											
							5.58		6.69											
							5.52		6.36											
							5.70		6.58											
8	February 26	21	4,100	2,611	6.4		6.18	6.20	7.24	7.14	2.31	159	6.9	5.5	11.5	7.5	864	53.4	4,108	21
							6.10		7.24											
							6.45		6.97											
							5.93		7.05											
							6.37		6.86											
									6.98											
									7.29											
									7.46											

9	March 9	27	5,150	2,690	6.6	0.79	5.40	5.48	6.32	6.31	2.25	195	8.6	11	11.0	7.0	1,005	73.6	5,660	18
					5.8	0.78	5.28		6.36											
							5.48		6.54											
							5.71		6.46											
							5.63		6.07											
							5.38		6.14											
									6.28											
10	March 16	22	4,200	2,529	9.3	0.10	5.69	5.23	6.04	6.53	3.90	244	6.4	14	14.0	9.0	951	59.8	4,600	21
					9.1	0.11	5.86		6.84						12.0					
							5.42		6.91											
							5.40		6.30											
							4.98		6.48											
							5.28		6.51											
							4.44		6.62											
							4.88		6.52											
							5.16		6.58											
11	March 21	36	2,900	1,921	6.8	0.86	5.74	5.63	6.26	6.69	2.94	183	6.2	7	13	10	1,035	52.3	4,040	25
					7.7	0.87	5.53		6.39					6	15					
							5.56		6.28											
							5.96		7.16											
							5.28		7.23											
							5.48		7.59											
							5.84		6.33											
							5.68		6.34											
12	April 4	32	3,550	2,138	5.9	0.79	5.82	5.62	5.94	6.26	1.80	198	11.0	4	14	10	1,833	58.0	4,460	41
					7.1	0.96	5.48		5.98					8.5	13.5					
							5.60		6.26											
							5.82		6.06											
							5.46		6.00											
							5.84		6.56											
							5.48		6.38											
							5.72		6.14											

TABLE 1—*Continued*

Number	Date	Age	Vital capacity	Vital capacity per square meter	Respiratory minute volume	Respiratory quotient	Alveolar CO_2 tension	Average alveolar CO_2 tension	"Virtual" venous CO_2 tension	Average "virtual" CO_2 tension	Difference arterial and venous CO_2 content	CO_2 elimination per minute	Circulation rate	Arm to heart circulation time	Crude pulmonary circulation time	Actual pulmonary circulation time	Amount blood in lungs	Weight of patient	Calculated blood volume	Total blood in lungs
	1927		*cc.*	*cc.*	*liters*		*volumes per cent*	*volumes per cent*	*volumes per cent*	*volumes per cent*	*volumes per cent*	*cc.*	*liters per minute*	*seconds*	*seconds*	*seconds*	*cc.*	*kgm.*	*cc.*	*per cent*
13	April 6	26	4,800	2,700	5.8	0.79	4.93	5.26	6.41	6.35	3.02	191	6.3	10	15	11	1,162	62.3	4,790	24
					5.9	0.78	5.57		6.46											
							5.16		6.57											
							5.16		6.13											
							5.21		6.33											
							5.87		6.48											
							5.09		6.20											
							5.12		6.36											
									6.22											
14	April 27	42	3,100	2,065	5.8	0.79	5.78	5.65	7.60	7.19	4.27	165	3.9	13	14	10	642	47.8	3,680	17
					6.1	0.85	5.77		6.56											
							5.60		7.71											
							5.79		7.56											
							5.58		7.27											
							5.72		7.19											
							5.53													
							5.47													

15	June 2	17	3,650	2,050	9.1 6.4	0.76 0.67	5.24 5.00 5.11 5.34 5.32 4.92 4.93 5.00	5.11	6.52 6.52 6.52 6.73 6.83 6.71 6.54 6.69	6.63	4.46	196	4.4	5.5	12	8	587	67.3	5,180	11
16	June 8	31	4,300	2,415	6.4 7.0	0.75 0.79	5.71 5.26 5.45 5.46 5.30 5.52 5.60 5.31	5.45	6.96 7.09 6.89 7.20 7.24 7.01 6.98 7.00	7.10	4.00	180	4.5	4	10	6	451	59.2	4,550	10
17	June 15	16	3,600	2,045	7.1 7.1	0.68 0.69	5.80 6.00 5.70 5.70 5.71 5.78 5.63 6.10	5.75	6.82 7.00 7.06 6.94 7.00 7.13 6.91 7.00 6.93	6.98	3.39	195	5.8	7	12	8	768	61.4	4,725	16

in the formula they are used as an expression of conditions existing simultaneously. The wide variation in the estimated quantity of blood in the lungs is, however, greater than the probable experimental error and suggests that the elasticity of the pulmonary tissue permits the accommodation of widely varying volumes of blood.

On the basis of our data, and assuming that the total blood volume of man is one-thirteenth of the body weight, the percentage of the total blood in the lungs was calculated. Wide variations were found in the amounts of blood in the lungs; the greater amounts were generally associated with slower blood flow. The average amount of blood in the lungs was, as has been said, 21 per cent of the total blood volume. No great weight is to be attached to the absolute values obtained though the results conform in general to those observed experimentally in animals. G. N. Stewart (3) observed that when both sides of the heart were completely obstructed simultaneously, the lungs in two animals contained respectively 21 and 18.6 per cent of the total blood volume. Similarly, Kuno (7), studying the heart lung preparation under various conditions found from 8.8 to 19.4 per cent of the total blood in the lungs. In animals, by using the pulmonary circulation time as a measure of the mean velocity, Stewart found 11 to 24 per cent of the total blood in the lungs. The average amount was 17 per cent.

On the basis of the data presented in this communication the estimated amount of blood in the lungs in man conforms so closely to the experimental results of Kuno and Stewart as to indicate that the pulmonary circulation time is an index of the mean time of blood flow through the lungs.

The fact that the pulmonary circulation time is such a close index of the mean time consumed by blood flow through the lungs, also indicates that "stringing out" effects caused by variations in the speed of blood flow through different pathways is not of great consequence in normal individuals, and that the different available pathways through the lungs are approximately equal.

CONCLUSIONS

1. Measurements of both the minute volume flow through the lungs and the pulmonary circulation time have been made in seventeen normal persons and the approximate amount of blood in the lungs has been calculated.

2. The average calculated amount of blood in the lungs was 984 cc., or approximately 21 per cent of the total blood volume. The quantity varies considerably in different individuals.

3. The results indicate that the pulmonary circulation time is an index of the mean time consumed by the blood flow through the lungs.

4. The observations suggest that in normal persons the available pulmonary pathways are approximately equal.

5. Normal variations in the pulmonary circulation time are not related to corresponding normal variations in the minute volume blood flow through the lungs.

6. The contention of von Kries and Tigerstedt is incorrect.

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