THE RESISTANCE TO THE BLOOD-FLOW. By HARRY CAMPBELL. (Three Figures in Text.)

THE resistance which the blood vessels offer to the circulation has to be considered from the physical and the physiological point of view.

VASCULAR RESISTANCE PHYSICALLY CONSIDERED.

This subject will be discussed under the following heads:

Capillary resistance,
Systemic resistance,
Pulmonary resistance,
The difference in the systemic and pulmonary resistance physically considered.

Capillary resistance. By a capillary I understand a blood vessel the walls of which are formed by endothelium only. It is generally taught that the capillaries offer very considerable resistance to the circulation. This view, I regard as untenable. On the contrary I believe that the capillaries normally oppose very little resistance to the blood-flow; and for the following reasons[1].

If these vessels offer much resistance there must be a corresponding fall of blood-pressure in them—*i.e.* the pressure at the arterial end of a capillary must be considerably greater than at the venous end. Now inasmuch as the capillary wall is very delicate and yielding, the effect of this difference of pressure would be to distend the proximal much more than the distal end, causing the capillary to become funnel-shaped. As a matter of fact it is cylindrical, and therefore the internal pressure must be much the same throughout its entire length. Such equality of pressure along the whole capillary is what we should expect: there can be no doubt that the interchange between the plasma of the blood and of the tissues is largely influenced by the amount of the capillary blood-pressure, and the assumption that the

[1] An article by the writer in favour of this view appeared in the *Lancet* 1894. Vol. 1.

pressure in the capillary falls rapidly, carries with it the assumption that this interchange differs considerably in different parts of the capillary—a most unlikely arrangement. Moreover, such a difference in the amount of pressure borne by the two extremities of the capillary would certainly be met by corresponding differences of structure: the vessel at the proximal end would be stouter and stronger than at the distal end; yet there is no evidence of this.

Again, if the resistance in the capillaries is great, how shall we account for the rapid emptying of the arteries into the veins upon extreme arterial dilatation?[1] This phenomenon is manifestly due to the removal of *arterial* resistance, unless indeed, we assume—and there are no grounds for such an assumption—that the capillaries share in the vaso-motor dilatation.

Finally, on the assumption that capillary resistance is great, how would it be possible for the blood in the portal vein, flowing as it does under a low pressure, to be driven through the capillary network of the liver?

We are driven therefore to the conclusion that the capillaries do not, normally, offer any great resistance to the blood-flow. Let us now inquire into the physical explanation of the fact.

The great shortness of the capillary must tend to keep down the resistance it offers. Assuming that the blood-pressure falls 200 mm. Hg in the entire circuit, and that the average length of the various systemic arcs is 1 meter, it is evident that for every millimeter of the circuit it will fall on an average $\frac{200}{1000} = \frac{1}{5}$ mm. Hg and for every half-millimeter (which is, at a high estimate, the average length of a capillary) $\frac{1}{10}$ mm. Hg. If, therefore, the blood-pressure fell equally along the entire circuit, the fall in the capillaries would be $\frac{1}{10}$ mm. Hg; and estimating the capillary fall as ten times this amount, the capillary resistance would only be equivalent to a fall of 1 mm. Hg.

Have we, however, any ground for assuming that the capillary-fall, and therefore resistance *is* ten times greater than the average fall and resistance? The one great factor tending to make capillary resistance high is the narrowness of the capillary lumen, but the influence of this has been strangely exaggerated by physiologists, notably by Marey.

[1] Rollett asserts that even after the heart has ceased to beat for half-an-hour, or longer, the stream in the capillaries still continues (Hermann's *Handb. der Physiologie*, IV. p. 317), and this suggests considerable resistance on the part of the capillaries. We must remember, however, that not only is the *vis a tergo* in such cases very small, but that the arterioles still offer considerable resistance.

Several factors tend to minimise it. Not only have we to take into account the extreme shortness of the capillary tube, but further (*a*) the slowness of the capillary flow, (*b*) the lowness of the capillary blood-pressure.

(*a*) The blood in the capillaries flows at an average rate of about 0·8 mm. per minute. It would be quite impossible with such a slow flow to get much friction, unless we assume a very great adhesiveness between the blood and the capillary wall, and there is no evidence that any normally exists.

(*b*) Blood-pressure plays an important part in determining resistance. The greater the one, the greater the other[1]. With so low a blood-pressure as 20—30 mm. Hg[2] it is unlikely that the friction between the blood and the capillary wall is great, unless we postulate a phenomenal adhesiveness between the two.

The factors, then, tending to keep capillary resistance low are: the shortness of the capillary, the slowness of the blood-flow in it, and the low level of its blood-pressure.

Physiologists in writing on capillary resistance would seem to imply that it is in direct proportion to the number of capillaries in the body. They continually refer to the enormous multitude of the capillaries, and to the great resistance which such a multiplicity of tubes must necessarily oppose[3]. As a matter of fact resistance is less in proportion

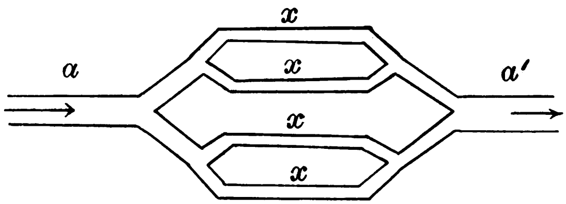

Fig. 1.

as the capillaries are numerous. In such a scheme of elastic tubes as is here represented (Fig. 1) the outflow of fluid through *a* is diminished

[1] The fact that an augmentation in blood-pressure augments resistance is apt to be lost sight of. The higher the blood-pressure, the greater is the pressure of the blood-particles against one another and against the vessel wall, and the greater therefore the internal and peripheral friction—just as the friction between two surfaces moving over one another increases with their pressure against one another.

[2] Authorities differ as to the actual amount of capillary blood-pressure. Its average amount is probably less than that given above.

[3] Even de Jager, who has so carefully studied the dynamics of the circulation, does not escape this error. He refers to "the enormous resistance the blood encounters at the end of the arterial system in the *numerous* and very small capillaries," (This *Journal* Vol. VII. p. 175).

by clamping any of the tubes x; as we multiply these latter the outflow tends to increase. If then we suppose a to represent an ultimate arteriole, a' its efferent venule, and x the capillary system connecting the two, we at once see that the more abundant the capillary network into which a opens, the greater will be the venous discharge, in other words, the more complex the capillary network, the less is the resistance. Were the ultimate arteriole connected with its venule by one, single, capillary, as Marey[1] erroneously assumes, the latter would oppose considerable resistance, for the flow through it would be many times more rapid than through the artery, and the friction per unit of vessel traversed by the blood would be so much the greater.

If, again, we suppose the sectional area of the capillary system to equal that of the arteriole, the resistance per unit of vascular circuit traversed would be greater in the former than in the latter, for while the rate of flow would be the same in each, the bore of the individual capillaries would be less, and the less the bore the greater the friction. If further we suppose the sectional area of the capillary system to increase, so as to become greater than that of the arteriole, a point will at length be reached when the diminution in resistance thus brought about more than counteracts the increase of resistance due to smallness of capillary bore, and the resistance per unit of capillary traversed becomes less than that per unit of arteriole traversed. Now seeing that the arteriole is very much longer than the capillary, the resistance in the former must be much greater than that in the latter.

Systemic Resistance. The amount of resistance which the blood

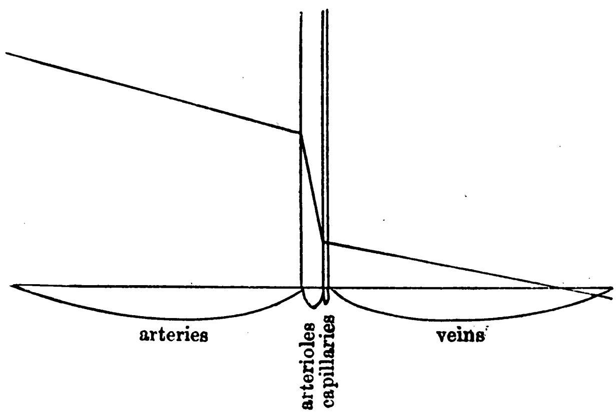

Fig. 2.

[1] *La Circulation du Sang.* Paris, 1881, pp. 158—159.

meets with in different parts of the systemic circuit is indicated by the way in which the blood-pressure falls in them. The accompanying diagram (Fig. 2) illustrates the fall of pressure. It is moderate in the large arteries; very marked in the arterioles; in the capillaries, it is probably inconsiderable; while in the entire venous system it is small. It will thus be seen that, if we cut the systemic system in two across the middle of the capillaries, the resistance in the proximal arterial half is very much more than that in the distal venous half. This fact has been accepted as a matter of course, but so far as I have been able to discover, no physiologist has thought it necessary to offer a full explanation[1]; and I therefore propose to make the attempt here.

Briefly, the chief factors in maintaining arterial resistance at a high level are:

The comparatively small bore of individual arteries.

The comparatively narrow bed of the arterial segment, leading to a comparatively rapid flow.

The comparatively small 'potential' capacity of the arterial segment, which coupled with the great resistance in the arterioles (due to smallness of arteriolar lumen and rapidity of arteriolar current) enables the blood-pressure in the arterial segment to go up, and this segment to be over distended. This high blood-pressure in the arterial segment increases the resistance through its entire extent, by increasing both internal and external (*i.e.* peripheral) friction. (See Footnote 1, p. 303.)

The chief factors in keeping venous resistance low are:

The comparatively large bore of individual veins.

The comparatively wide bed of the venous segment, causing a correspondingly slow current.

The comparatively large 'potential' capacity of the venous segment, which prevents the venous segment from being distended, and consequently the venous blood-pressure from being high. The venous pressure being low, internal and external friction are kept correspondingly low.

[1] Probably the greater resistance offered by the arterial half has been tacitly attributed, at any rate, in large measure, to the great resistance which is supposed to exist in the capillaries. But even if the resistance in the capillaries be great, it does not explain why the arterial segment offers so much more resistance than the venous; for it will be seen that I have supposed the systemic system to be divided *through the middle of the capillaries* and the capillary resistance to be similarly divided, one half belonging to the proximal and the other half to the distal segment.

Pulmonary Resistance. The resistance in the several parts of the pulmonary segment differs considerably from that of the corresponding parts of the systemic segment, as shown by comparing the manner in which the blood-pressure falls in the two. It will be observed (see Fig. 3) that while in the systemic segment the fall is much greater in the proximal than in the distal half, showing that the resistance is correspondingly greater, in the pulmonary segment the fall is much the same in the two halves of the segment, showing that the resistance in each is much more nearly the same.

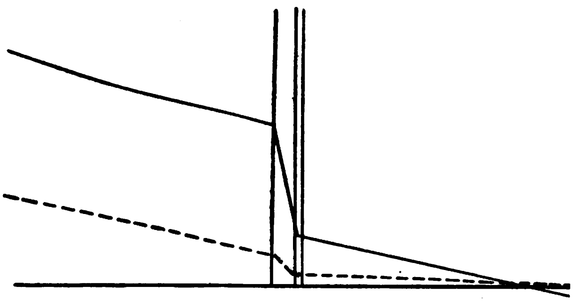

Fig. 3. The continuous line represents the fall of blood-pressure in the systemic segment; the dotted line shows its fall in the pulmonary segment.

The fall is, as a matter of fact, somewhat greater in the arterial half, this extra resistance residing in the arterioles; but it is only slightly greater, and although the descent is probably somewhat rapid in the arterioles, it is on the whole gradual and regular throughout the entire segment. The venous pressure, moreover, never sinks below zero, as in the case of the systemic segment, the blood entering the left auricle under a positive pressure.

The peculiar disposition of resistance in successive sections of the pulmonary segment is explained by the following facts:—

1. The capacity, actual and potential, of the two halves of the pulmonary segment being equal, the mean rate of blood-flow is the same in each, and this tends to make the resistance in the two the same.

2. The bore of the individual arteries is much the same as that of the corresponding veins. This also tends to make the resistance in each segment the same. The pulmonary arterioles are, however, smaller (during life, at all events) than the corresponding veins, and therefore offer a greater resistance.

3. The special resistance in the pulmonary arterioles, by raising the

blood-pressure behind causes the resistance in the proximal portion to be so much the greater.

The Ratio between Systemic and Pulmonary Resistances physically considered.

No physiologist has, so far as I know, satisfactorily explained either on physical or physiological grounds, the great excess of systemic over pulmonary resistance. The first explanation (physical) which suggests itself, and, that tacitly assumed by the text-books, has reference to the (*a*) larger size and (*b*) the greater complexity of the systemic vascular area.

(*a*) The systemic system is some fourteen times more capacious than the pulmonary, and it is assumed that, on this account, it necessarily offers the greater resistance. Such an assumption is, however, the very reverse of the truth. The relative smallness of the pulmonary circuit operates in the direction of increasing resistance in it, seeing that the smaller the "bed," the more rapid the flow and seeing moreover that friction increases with rate of flow. We know from clinical experience that the destruction of pulmonary tissue, with the resulting shrinkage in vascular area, augments resistance and casts extra work on the right heart; but in order fully to appreciate the fact that resistance tends to vary inversely with vascular capacity, let us suppose the pulmonary segment to be made up of the systemic pulmonary vessels only—*i.e.*, the bronchial, and then imagine the enormous resistance it would oppose to the right heart, and the enormous force that would be required to drive through it, in a given time, the same quantity of blood as passes through the systemic segment! Under these circumstances the right heart would require to be some scores of times more powerful than the left.

(*b*) The systemic vascular tree being very much more complex than the pulmonary, it is assumed that it must necessarily oppose more resistance. There is a great tendency to assume that a system of tubes, like the arteries, dividing and subdividing and eventually breaking up into an enormous capillary network, connected with a second system of tubes which keep uniting into larger and ever larger tubes, like the veins, must of necessity offer considerable resistance to the blood-flow. Such is, however, not the case. We have seen that the resistance in a system of tubes may be actually diminished by increasing the number of subdivisions. And that a highly complex system of tubes does not necessarily oppose great resistance to the fluid circulating in it is made manifest by the slight resistance which the liver opposes to the portal blood, and by the facility with which the blood passes from the systemic arteries into the veins directly marked arterial dilation occurs.

We have explained, on physical grounds, why the systemic segment offers greater resistance than the pulmonary, and why therefore the left heart is stronger than the right. The difference in the resistance offered by the two segments is represented by the difference between the aortic and pulmonary blood-pressure, which has been variously estimated at from 1 : 5—3 : 5.

1. The vessels constituting the arterial half of the pulmonary segment have a larger bore than the corresponding systemic vessels[1]. This is the great cause of the excess of systemic over pulmonary resistance.

Not only are the pulmonary arterioles larger than the systemic arterioles when each set is completely relaxed, but it is certain that their mean lumen during life is larger than that of the systemic arterioles, owing to the greater vasomotor activity in the latter case.

The pulmonary capillaries are smaller in bore than the vast majority of systemic capillaries[2], but since capillary resistance is slight, this fact does not appreciably increase pulmonary resistance. Nevertheless I believe that the resistance in the pulmonary capillaries is appreciably greater than that in the systemic capillaries, not only on account of the smaller bore of the former, but because the blood-flow is more rapid in them than in the systemic.

2. The pulmonary vessels are shorter than the systemic. This difference may at first sight appear to be the chief cause of the great difference in the resistance in the two circuits. I do not, however, believe it to be so, many considerations making it obvious that length of circuit need have little influence on resistance: (*a*) The length of the systemic circuit is chiefly determined by the length of the larger vessels, such as (on the arterial side) the aorta, the brachials, and femorals. Now, while there can be little doubt that long, narrow

[1] This conclusion I arrived at *a priori*, and have since found substantiated by Ewart's work on the anatomy of the lungs. Ewart refers only to the comparatively large bore of the main trunks, but I think we may also conclude that the smaller vessels share in this peculiarity.

[2] It used to be taught that the pulmonary capillaries are exceptionally large, and that this is the chief factor in causing pulmonary resistance to be less than systemic.

vessels, like the spermatic, offer considerable resistance, such is not the case with the large arteries in which the blood-pressure falls very gradually. (*b*) If mere length of circuit played a large part in causing resistance, the systemic veins of such animals as the giraffe and the whale would offer an unusually great resistance; but they do not. (*c*) Further, on this assumption we should expect to find a greater disproportion between the strength of the two sides of the hearts in animals which like the giraffe possess a long systemic circuit in proportion to their weight than obtains in such an animal as the rabbit, for instance, but I am not aware that any such disproportion exists. (*d*) Nothing more conclusively shows the slight influence of length of circuit on resistance than the comparatively small difference in systemic resistance, as determined by carotid pressure, in animals differing greatly in size, thus while the carotid pressure of the horse varies from 160 to 200 mm. Hg, that of the sheep, with a much shorter circuit, varies between 155 and 210 mm. Hg.

3. If we take successive transverse sections of each circuit we find that the mean 'bed' of the pulmonary circuit is much smaller than that of the systemic: hence the mean rate of flow is much greater in the former. This tends to make pulmonary resistance greater than systemic.

I have, I repeat, no doubt that the essential cause (physical) of the excess of systemic over pulmonary resistance lies as I have already said in the difference in the mean bore of the vessels constituting the proximal half of each circuit. The comparatively large size of these in the case of the pulmonary circuit so far reduces resistance as to much more than neutralize the influence in augmenting resistance of the comparatively narrow pulmonary bed.