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OBSERVATIONS ON THE PUMPING ACTION OF THE HEART.

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A STUDY of the factors which influence the systemic flow is complicated by the number involved and by their interaction. In general it may be stated that the pumping action of the heart and the state of the peripheral circulation are the chief factors determining the systemic flow. Starling and his co-workers [1912, 1914] laid down the principles which govern the pumping action of the heart in the heart-lung preparation, one of them being that a healthy heart maintains the venous pressure at zero for inflows up to 1 litre per min. It is desirable therefore to enquire whether the heart in the body reacts to all changes in the peripheral circulation by maintaining the venous pressure constant. The object of this paper is to describe experiments showing that the same order of change in the systemic flow is produced by occlusion of certain systemic blood vessels, whether the heart or a pump maintaining the venous pressure constant is the motive force for driving the blood through the circulation. The results of the investigations suggest that the heart in the body reacts to certain systemic circulation phenomena by adjusting its output so as to maintain the venous pressure constant, and in this respect therefore behaves like the heart of the heart-lung preparation.

I. Description of preparation in which a pump replaced the heart.

In the preparation about to be described the delivery of the pump was regulated so as to maintain the venous pressure as nearly constantly at zero as possible under all conditions. An electrically-driven Albany No. O rotary pump was found to fulfil this purpose admirably.

Dogs weighing approximately 10 kg. were used. Fig. 1 shows a diagram of the preparation.

Blood flowed from the S.V.C. (*B*) and the I.V.C. (*D*) to a small reservoir *F*. At the same time blood was drawn from the reservoir by the pump *G*. From the pump it passed through a heating spiral *H* and a mechanical stromuhr *J* [Barcroft, 1929]. The arterial blood-pressure was recorded by a mercury manometer attached at *K*. The temperature of the blood was taken at *L* and was maintained at 37° C. Finally the blood entered

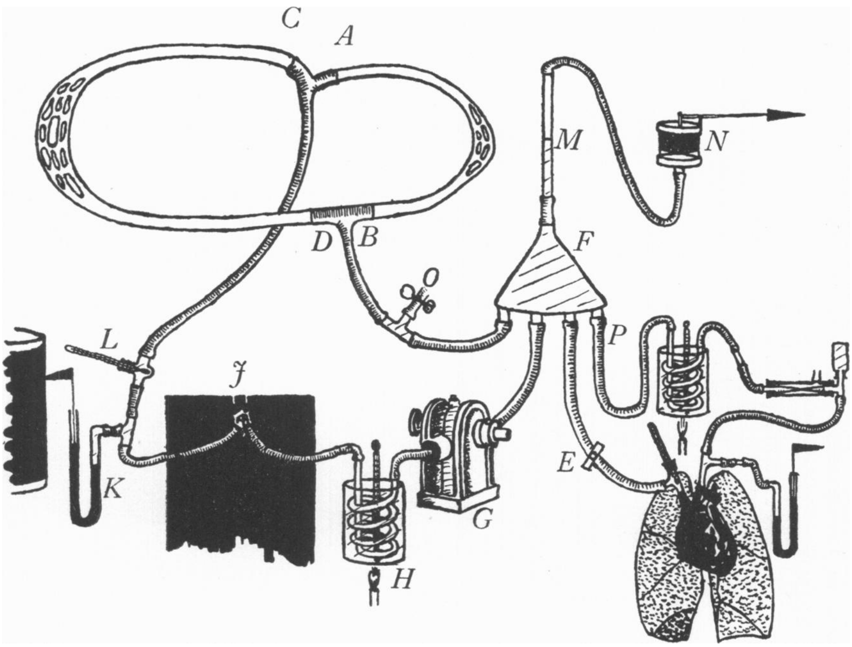

Fig. 1. Diagram of preparation in which a pump replaced the dog's heart. *A*, brachiocephalic artery; *B*, S.V.C.; *C*, thoracic aorta; *D*, I.V.C.; *O*, burette; *F*, blood reservoir; *M*, tube above reservoir for regulating venous blood-pressure; *N*, piston recorder; *E* and *P*, tubes to and from heart-lung preparation; *G*, pump; *H*, heating spiral; *J*, mechanical stromuhr; *K*, arterial blood-pressure manometer; *L*, thermometer.

the brachiocephalic artery at *A* and the thoracic aorta at *C*. The pressure of the blood in the reservoir *F* was measured by the height of the blood in the narrow tube *M*. The reservoir was placed so that a mark on the tube *M* represented the level of the disused heart in the animal. When the blood was at this level the venous pressure was therefore approximately zero. The output of the pump was regulated so as to maintain the blood level at the mark on the tube *M* under all conditions. A piston recorder *N* showed graphically whether the experimenter had been successful in keeping the blood level constant. At the beginning of the experiment blood was added through the burette attached at *O* till the arterial blood-pressure was 80 mm. of mercury.

The arrangements for oxygenating the blood were as follows. Blood flowed from the reservoir *F* through the tube *E* to a heart-lung pre-

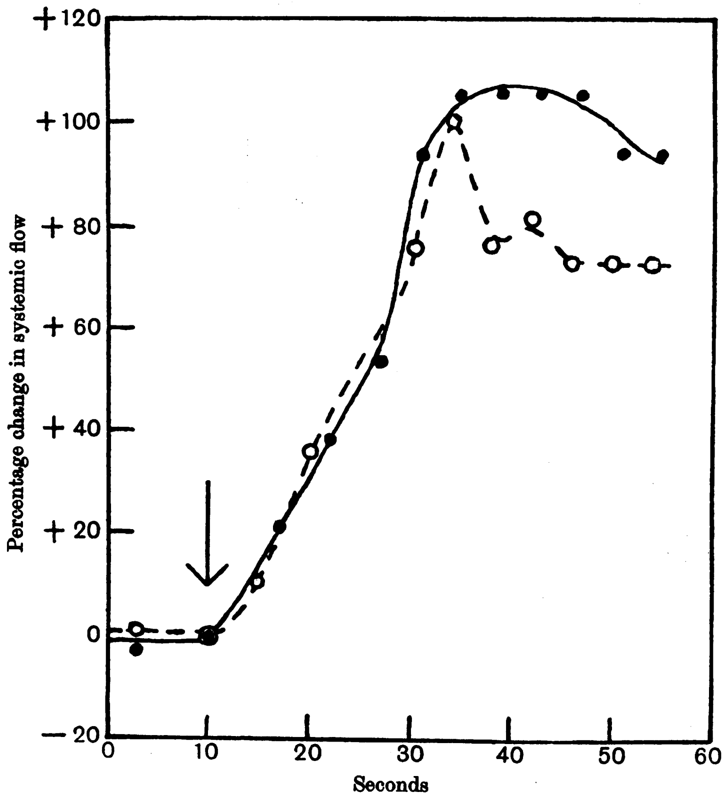

Fig. 2. Variations in the systemic flow in the animal and in the pump preparation after the injection of 50 c.c. blood. Continuous line: Animal. Initial flow, 530 c.c. per min. Broken line: Pump preparation. Initial flow, 440 c.c. per min. The injection was made at the time indicated by the arrow.

paration. Oxygenated blood from the heart-lung preparation returned to the reservoir *F* through the tube *P*. Thus oxygenated blood entered the reservoir *F* continuously and mixed with the blood returning from the animal. As the pressure in the reservoir *F* was maintained constant the flow to and from the heart-lung preparation was constant.

II. Variations in the systemic flow in the animal and in the preparation in which the pump replaced the heart.

A full account of the study of certain variations in the dog's systemic flow has been given in a previous paper [Barcroft, 1931]. Typical

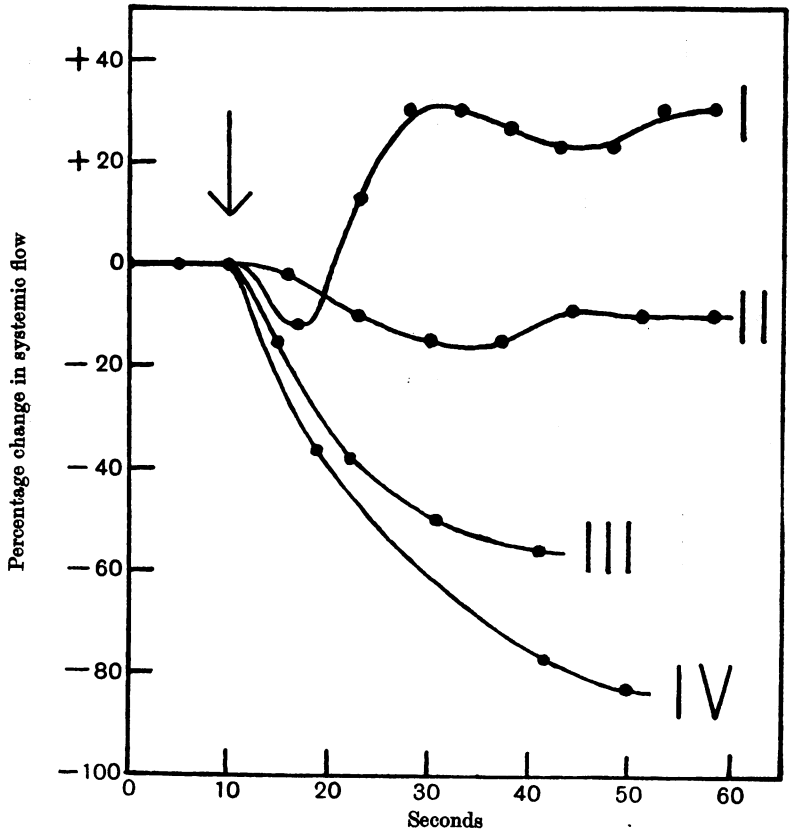

Fig. 3. Variations in the systemic flow in the animal after occlusion of a great vessel. Curve I: Occlusion of the thoracic aorta. Initial flow, 600 c.c. per min. Curve II: Occlusion of the brachiocephalic artery. Initial flow, 460 c.c. per min. Curve III: Occlusion of the s.v.c. Initial flow, 860 c.c. per min. Curve IV: Occlusion of the I.V.C. Initial flow, 680 c.c. per min. Each occlusion was made at the time indicated by the arrow.

examples are shown in the figures here. These variations were obtained in animals after section of the vagi, and after destruction of the brain.

Two experiments have been performed, using the preparation in which the pump replaced the heart. Uniform results have been obtained. Typical examples are shown.

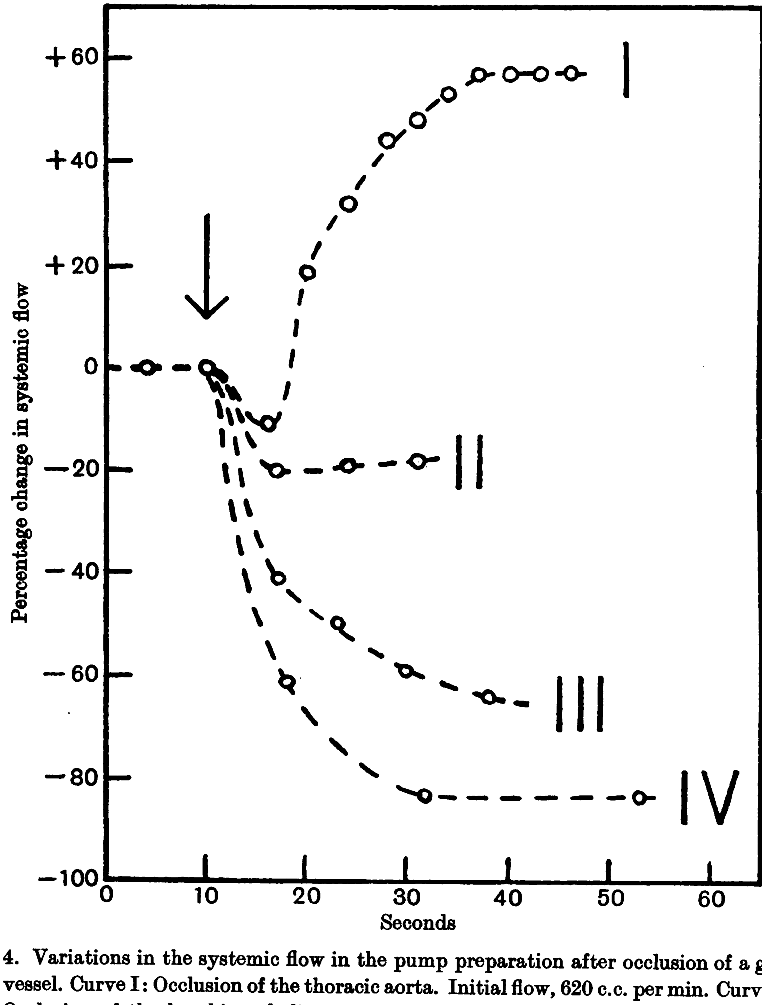

Fig. 4. Variations in the systemic flow in the pump preparation after occlusion of a great vessel. Curve I: Occlusion of the thoracic aorta. Initial flow, 620 c.c. per min. Curve II: Occlusion of the brachiocephalic artery. Initial flow, 540 c.c. per min. Curve III: Occlusion of the s.v.c. Initial flow, 560 c.c. per min. Curve IV: Occlusion of the I.V.C. Initial flow, 490 c.c. per min. Each occlusion was made at the time indicated by the arrow.

(1) *Injection of blood.*

Fig. 2 shows that 50 c.c. of blood injected into the vascular system increased the systemic flow in the animal and in the pump preparation.

In the animal the blood was added through a burette attached to the femoral vein. In the pump preparation it was added through a burette attached at *O* (Fig. 1).

(2) *Occlusion of one of the great vessels.*

Fig. 3 shows variations in the systemic flow in the animal after occlusion of one or other of the great vessels. Typically the systemic flow

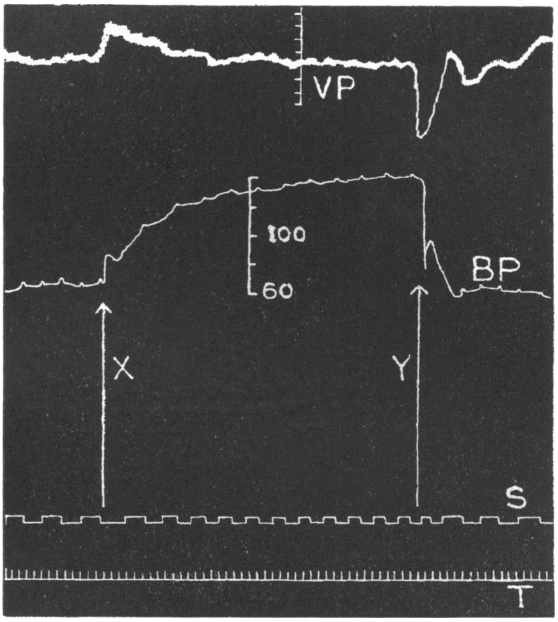

Fig. 5. Tracing taken during experiments using pump preparation. The thoracic aorta was occluded at *X* and released at *Y*. V.P. Venous blood-pressure. Scale cm. of water. B.P. Arterial blood-pressure. Scale mm. of mercury. S. Stromuhr, 26 c.c. of blood passed through the instrument between successive strokes. T. Time in seconds.

was increased by occlusion of the thoracic aorta (curve I), slightly decreased by occlusion of the brachiocephalic artery (curve II), moderately decreased by occlusion of the S.V.C. (curve III) and greatly decreased by occlusion of the I.V.C. (curve IV).

Fig. 4 shows that in the pump preparation comparable occlusions produced comparable changes in the systemic flow. The great vessels were occluded at the positions marked by *A*, *B*, *C* and *D* in Fig. 1.

A tracing of the events recorded in the pump preparation experiments during occlusion of the thoracic aorta is shown in Fig. 5. The occlusion was made at X. The venous pressure rose sharply; this is shown in the top tracing. The pump was adjusted to bring the venous pressure back to its original level. This resulted in an increase in the arterial blood-pressure and in the systemic flow. The small jerks in the blood-pressure tracing are due to the reversal of the blood stream through the stromuhr.

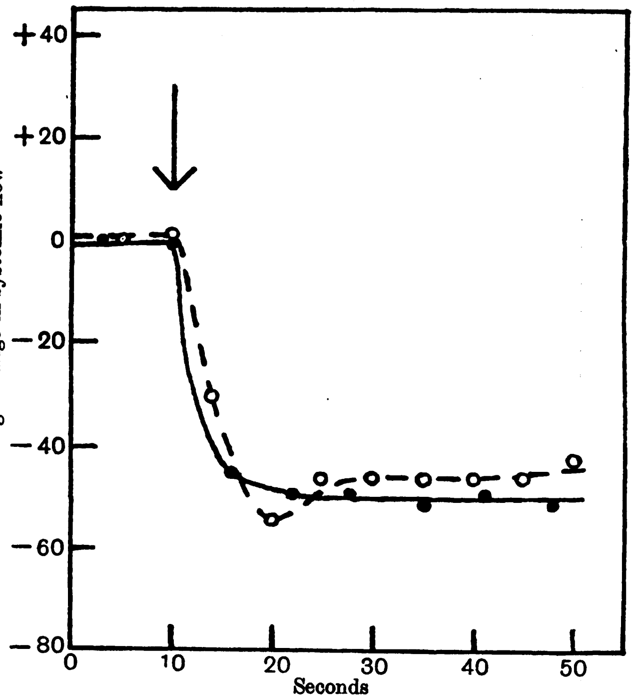

Fig. 6. Variations in the systemic flow in the animal and in the pump preparation after simultaneous occulsion of the thoracic aorta and the I.V.C. Continuous line: Animal. Initial flow, 410 c.c. per min. Broken line: Pump preparation. Initial flow, 590 c.c. per min. The occlusions were made at the time indicated by the arrow.

(3) *Simultaneous occlusion of the thoracic aorta and* I.V.C.

This procedure caused a considerable decrease in the systemic flow in the animal and in the pump preparation as shown in Fig. 6.

III. Discussion.

The comparable behaviour of the systemic flow in the animal and in the pump preparation leads to the conclusion that the principles governing the action of the heart and of the pump were the same. Hence the principles governing the pumping action of the heart in the animal were those enunciated by Starling for the heart in the heart-lung preparation.

IV. Description of operation for replacing the heart by the pump.

Blood was first obtained from two dogs, each weighing as much as possible. Two litres were sufficient.

Two other dogs, each weighing approximately 10 kg., were used in each preparation. Morphia was given. Equal parts chloroform and ether were used as anæsthetic.

Operation on the first animal. The first animal was used to prepare a heart-lung preparation. This preparation is described by Knowlton and Starling [1912]. The usual form of apparatus was used and was slightly elaborated as follows. The tube *E*, Fig. 7, opened into the tube leading from the heart-lung venous reservoir to the heart of the heart-lung preparation. At this stage of the operation it was clamped at *E*. The tube *P*, Fig. 7, opened into the tube leading from the finger-stall resistance to the venous reservoir of the heart-lung preparation. At this stage of the operation it was clamped at *P*.

Operation on the second animal. The animal was anæsthetized. Artificial respiration was established, using a Palmer's Ideal pump. Anæsthetic was administered through the pump as required. The thorax was opened along the mid-line. The internal mammary arteries, mediastinal vessels and thymus were cut between ligatures. The thoracic wall was divided on both sides between the fourth and fifth ribs. The ribs were drawn widely apart and secured. Two ligatures were placed round the I.V.C. The azygos vein was tied. Two ligatures were placed round the S.V.C. Two ligatures were placed round the brachiocephalic artery. The subclavian artery was tied between the aorta and the vertebral artery. A ligature was placed round the arch of the aorta below the subclavian artery. A ligature was placed round the aorta $1\frac{1}{2}$ in. below the ligature on the arch of the aorta. A ligature was placed round all the intercostal vessels arising from the aorta between the two ligatures round the aorta. A cannula leading to a burette was placed in the left auricular appendix. 0·25 g. of heparine in approximately 10 c.c. warm saline was injected through the burette. The arrangement of tubes and cannulæ attached to the pump and stromuhr is shown in Fig. 7. Artery forceps were placed initially at *B*, *C*, *F*, *G*, *P* and *E*. The whole apparatus was filled with blood at 40° C. This was added through the burette (Fig. 7). To assist this the pump was started at appropriate intervals, and air expelled by loosening the artery forceps. The spiral was placed in a gas-heated water bath. The apparatus was attached to the animal as follows.

The upper ligature on the I.V.C. was tied. The cannula *H* was inserted peripherally and tied in by the lower ligature. The artery forceps at *C* was removed. The lower ligature on the S.V.C. was tied. The cannula *J*

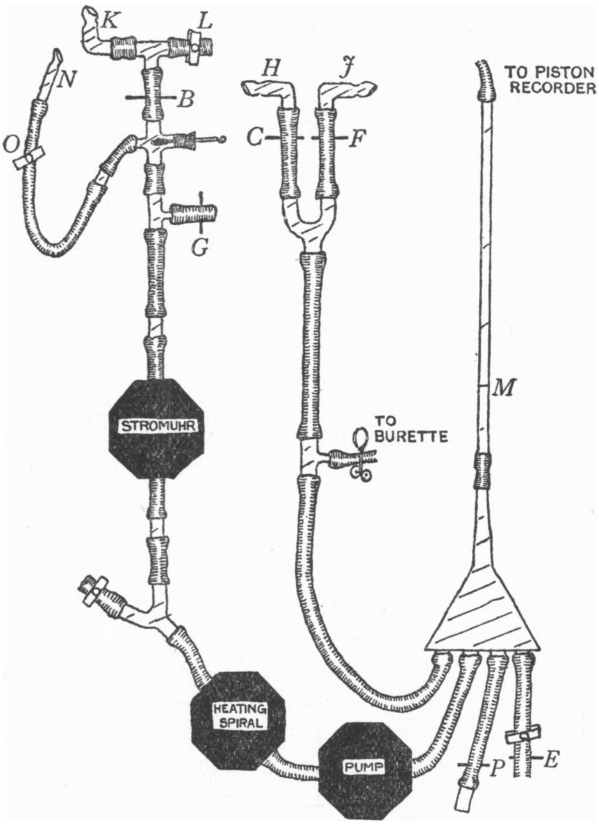

Fig. 7. Apparatus used in the experiments in which the dog's heart was replaced by a pump. Detailed explanation in text.

was inserted peripherally and tied in by the upper ligature. The artery forceps at *F* was removed. The ligature on the arch of the aorta was tied. A bull-dog clip was placed on the thoracic aorta below the lowest ligature and tightened. The cannula *K* was inserted peripherally, above the bull-dog and was tied in by the lower ligature. The artery forceps at *B* was removed. The pump was turned over a few times and air in the aortic cannula was driven out through the tube *L*. The clamp at *L* was then tightened, and the bull-dog on the thoracic aorta removed. The arterial blood-pressure manometer was attached at *G*. The pump was started. Warm blood was added through the burette (Fig. 7) till the blood-pressure was 80 mm. of mercury and the blood was at the marked level in the tube *M* (Fig. 7). The lower ligature on the brachiocephalic artery was tied. The cannula *N* was inserted peripherally and tied in by the upper ligature. The screw clip at *O* was removed. The circulation of oxygenated blood from the heart-lung preparation through the reservoir was then established. The artery forceps at *P* and *E* were simultaneously removed, and were placed so as to prevent the blood entering or leaving the heart-lung venous reservoir. The flow through the heart-lung preparation was suitably adjusted by the screw clamp at *E*. The ligature round the intercostal vessels was tied. The preparation was now ready for the experiment.

The circulation in the animal was suspended for a few minutes after the ligatures on the venæ cavæ had been tied. During this period the brain was destroyed by asphyxia. By modifying the above technique this could have been avoided. Such a precaution was unnecessary, as the variations in the systemic flow studied were found alike in the animal with the vagi cut and the brain destroyed [Barcroft, 1931].

SUMMARY.

1. The systemic flow has been studied in the dog and in a preparation in which a pump replaced the dog's heart.

2. The output of the pump was adjusted so as to maintain the venous pressure approximately constant under all conditions. In this respect its action imitated the action of the heart in the heart-lung preparation under certain conditions described by Starling.

3. The behaviour of the systemic flow under a variety of conditions was found to be the same in the animal and in the pump preparation.

4. The conclusion drawn from these experiments is that, under the conditions studied, the animal's heart reacted to artificial changes in the peripheral circulation by adjusting its output so as to maintain the venous pressure approximately constant.

I am very grateful to Prof. Barcroft for much kind help in this research.

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