Thorax (1957), **12**, 208.

THE HYPOTHERMIC HEART*

WORK POTENTIAL AND CORONARY FLOW

BY

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Surgery of the heart and great vessels of necessity imposes a burden on an already diseased heart. Whether hypothermia as an ancillary technique adds a further load to the heart is of fundamental importance and therefore the effect of cooling on myocardial contractility was investigated. This was determined by the use of modified Starling curves (relation of stroke work to filling pressure) as described by Sarnoff and Berglund (1954). The behaviour of coronary flow and filling pressures in relation to other physiological variables was also studied.

METHOD

Dogs premedicated with morphine (2 mg./kg.) were anaesthetized with a 1:10 chloralose-urethane solution given intravenously. The chest was opened in the fifth left interspace, occasionally with the resection of the fifth rib, and respiration was maintained by constant volume, intermittent positive pressure from a Starling pump. The circulation was rearranged according to the method of Sarnoff and Berglund (1954), with the addition of measurement of coronary flow (Case, Berglund, and Sarnoff, 1954). Blood leaving the left ventricle enters the aorta from which it flows through a Potter electroturbinometer (Sarnoff and Berglund, 1953) to the descending aorta and brachiocephalic artery. A side arm proximal to the electroturbinometer leads blood through a recording rotameter (Shipley and Wilson, 1951) from which it flows into a modified Gregg coronary cannula. The tip of this has been passed into the aorta via the left subclavian artery and then tied in the left main coronary artery. Thus the total cardiac output was measured except for blood entering the right coronary artery.

Pressures were measured in the left and right atria, and in the pulmonary artery and aortic arch by means of electromanometers, and, with the coronary flow and cardiac output, were continuously and simultaneously recorded on a Sanborn direct-writing oscillograph. Clotting was prevented with "treburon." Blood increments of 50 to 100 ml. were added to the femoral vein at regular intervals resulting in increases in all flows and pressures. In this way, data were gathered for the calculation of left ventricular function curves.

Left ventricular stroke work in gram-metres was calculated by multiplying stroke volume in cubic centimetres by the difference between mean arterial and mean left atrial pressure in cm. of water and dividing by 100. Left ventricular function curves were obtained by plotting the stroke work of the left ventricle against its simultaneous mean left atrial pressure over the whole range of atrial pressures.

After this information had been obtained at 37° C. the animal was cooled to 28° C. by passing blood from the femoral artery to the femoral vein through a coil immersed in ice water (Delorme, 1952). Measurements were not made while this shunt was functioning. Rewarming was accomplished by immersing the coil in water at 45° C. Temperature was measured by a standardized mercury thermometer inserted into the aortic blood stream. The data for ventricular function curves were then gathered at 28° C. as previously described and again after rewarming.

In three dogs, complete A-V dissociation was obtained by ligation of the bundle of His three weeks before performing the experiments described herein. The ligation is a modification by Borst (personal communication) of the technique of Starzl, Gaertner, and Baker (1955). In these dogs heart rate was controlled by electrical stimulation of the left ventricular myocardium.

RESULTS

Nine successful preparations were obtained. Left main coronary flow was measured in two and the rate was controlled by electrical stimulation in three.

COOLING CURVES.—Results obtained during cooling, which are typical of the data obtained in all animals, are presented in Fig. 1. Filling pressures remained essentially the same while stroke volume rose. Other values fell as expected.

*Presented in part at the Second European Congress of Cardiology, Stockholm, 1956.

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left coronary flow decreasing relatively more than aortic pressure. For example, in the experiment shown in Fig. 1, heart rate fell 46%, aortic pressure 55%, cardiac output 31%, while coronary flow fell 77% and stroke volume rose 25%.

VENTRICULAR FUNCTION CURVES.—As blood was transfused, aortic pressure rose to approximately the same levels at 28° C. as at 37° C. at equivalent filling pressures. However, cardiac output rose relatively less at 28° C., presumably due to the lower heart rates at the lower temperature. In Fig. 2, for example, heart rate at 37° C. fell from 200 to 140 during blood transfusion, while at 28° C. it fell from 115 to 100. Coronary flow rose less during hypothermia. Ventricular function curves were approximately the same, or occasionally higher at 28° C., as compared with those obtained at 37° C. in the same dog, indicating an equal or greater contractility of the myocardium in the hypothermic state (Fig. 2).

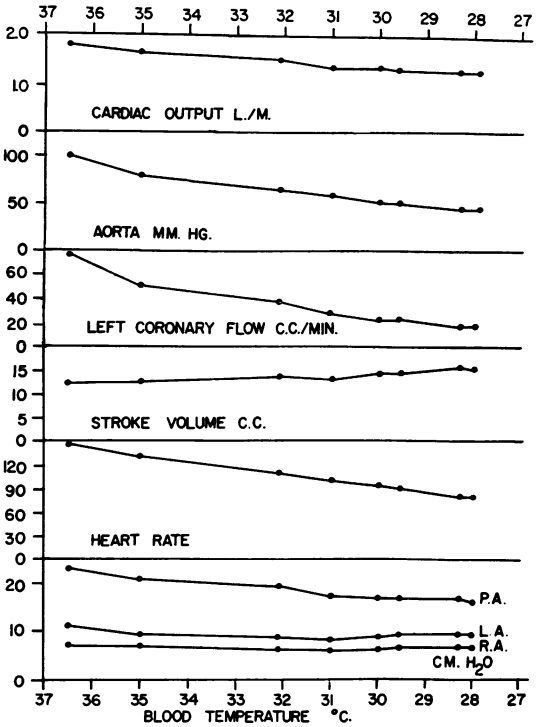

FIG. 1

FIG. 1.—Simultaneous and continuous measurement of: (1) cardiac output, (2) mean aortic pressure, (3) left coronary artery flow, (4) stroke volume of the heart, (5) heart rate, (6) pulmonary arterial and left and right atrial pressures in a 25-kg. dog during cooling from 37° C. to 28° C.

FIG. 2.—Left ventricular function curve of a 25 kg. dog plotted at 37° C. and 28° C. Abscissa shows left atrial mean pressure in cm. water. Ordinate shows left ventricular stroke work in gram-metres.

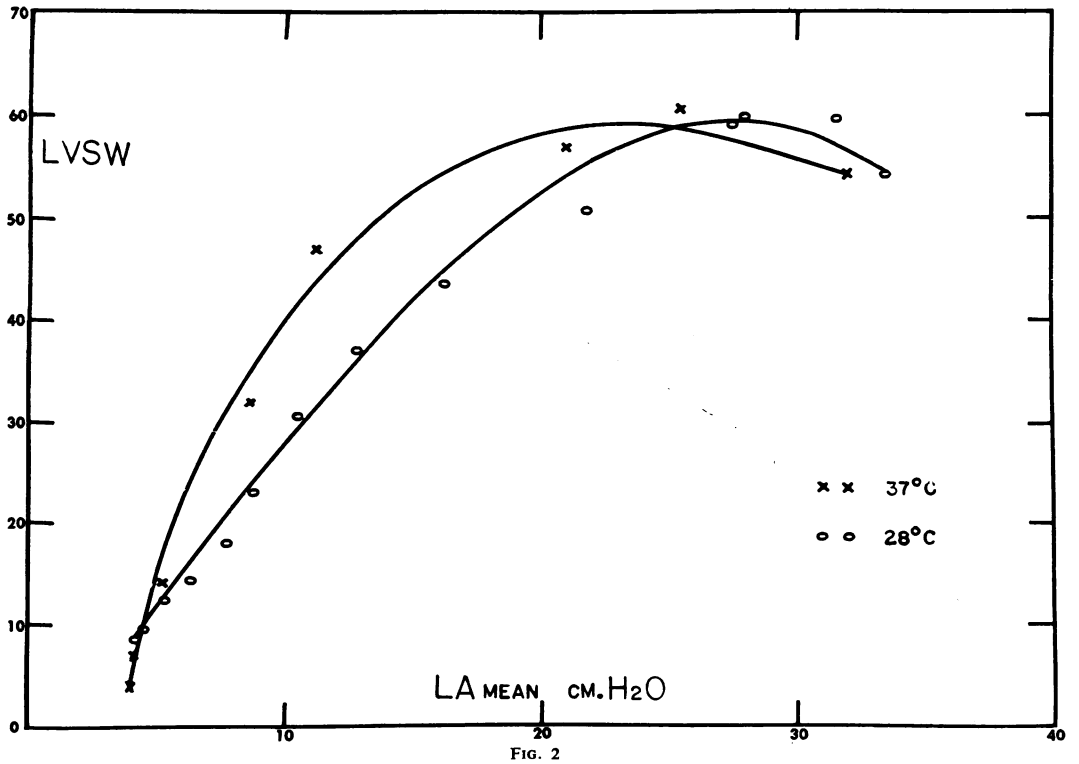

FIG. 2

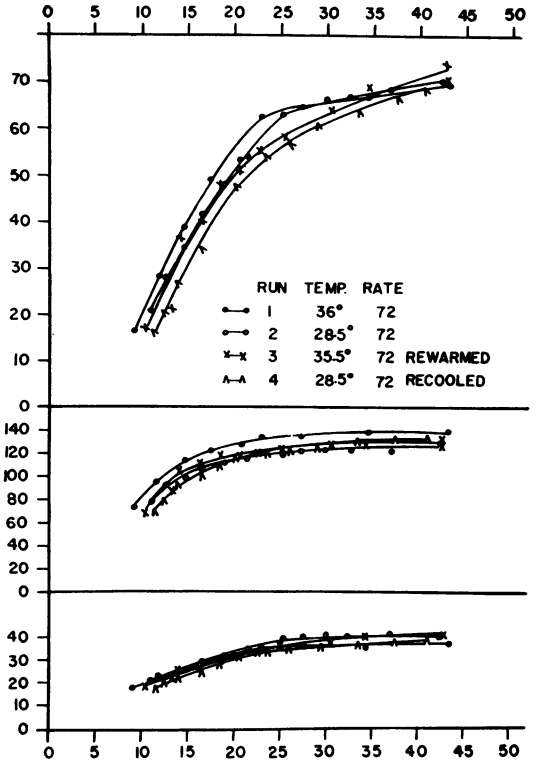

FIG. 3.—*Top:* Left ventricular stroke work in gram-metres. *Middle:* Mean aortic pressure in mm. Hg. *Bottom:* Stroke volume in c.c. All three plotted against left atrial mean pressure. This figure shows four separate curves plotted from the same dog at different temperatures with the heart rate held constant.

Curves obtained at identical heart rates (Fig. 3) show that the function curve is virtually the same at 28° C. and 37° C. under these conditions and that increases in stroke volume and aortic mean pressure were also similar.

The upper part of Fig. 4 shows the effect of heart rate on the ventricular function curve at 37° C. In this experiment, heart rate was controlled and maintained constant throughout each curve at 70, 100, and 125 beats per minute. The curve is seen to be depressed slightly as the rate is increased, as has been previously observed (Berglund, Duff, and Borst, to be published).

The lower half of Fig. 4 shows curves obtained at similar rates but at 28° C. in the same animal. The curve is seen to fall off slightly at a rate of 100, and to fall severely at a rate of 125. A curve repeated at a rate of 70 is identical with the first curve at 70, showing that the falling off is entirely due to an alteration in rate and not to deterioration of the preparation.

CORONARY FLOW.—Fig. 5 is a plot of left ventricular minute work against left main coronary flow as measured during transfusions at 37° C. and 28° C. It may be seen that at lower work levels the performance of a given amount of work is accompanied by lowered coronary flows at reduced temperature.

The third curve shows no appreciable drift after hypothermia to 28.7° C. has been maintained for 40 minutes.

DISCUSSION

A. COOLING CURVES.—The simultaneous, continuous recording of the seven variables presented in Fig. 1 gives a composite picture of the physiological changes occurring during the induction of hypothermia. Regardless of the number of points taken from the recordings there were no sudden changes in these values during cooling.

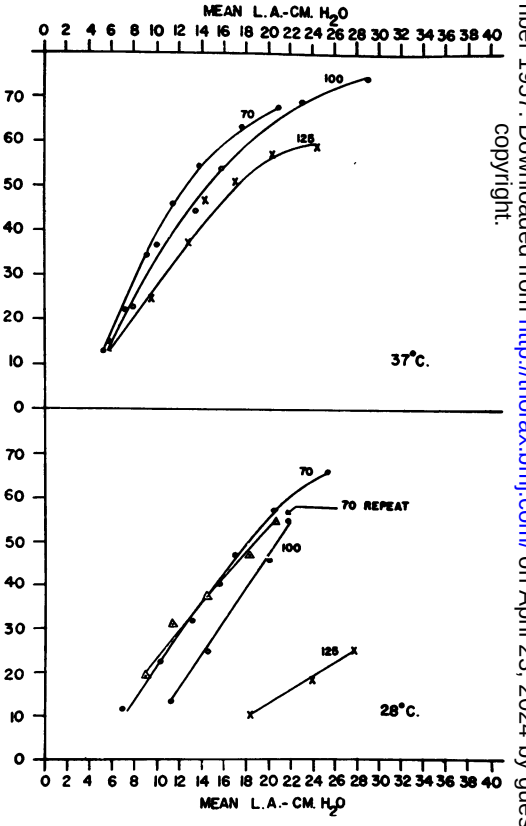

FIG. 4.—Left ventricular stroke work (in gram-metres) plotted against mean left atrial pressures (cm. water) at 37° C. (top figure) and 28° C. (bottom figure) showing the effect of increasing the heart rate on the ventricular function curves at these two temperatures.

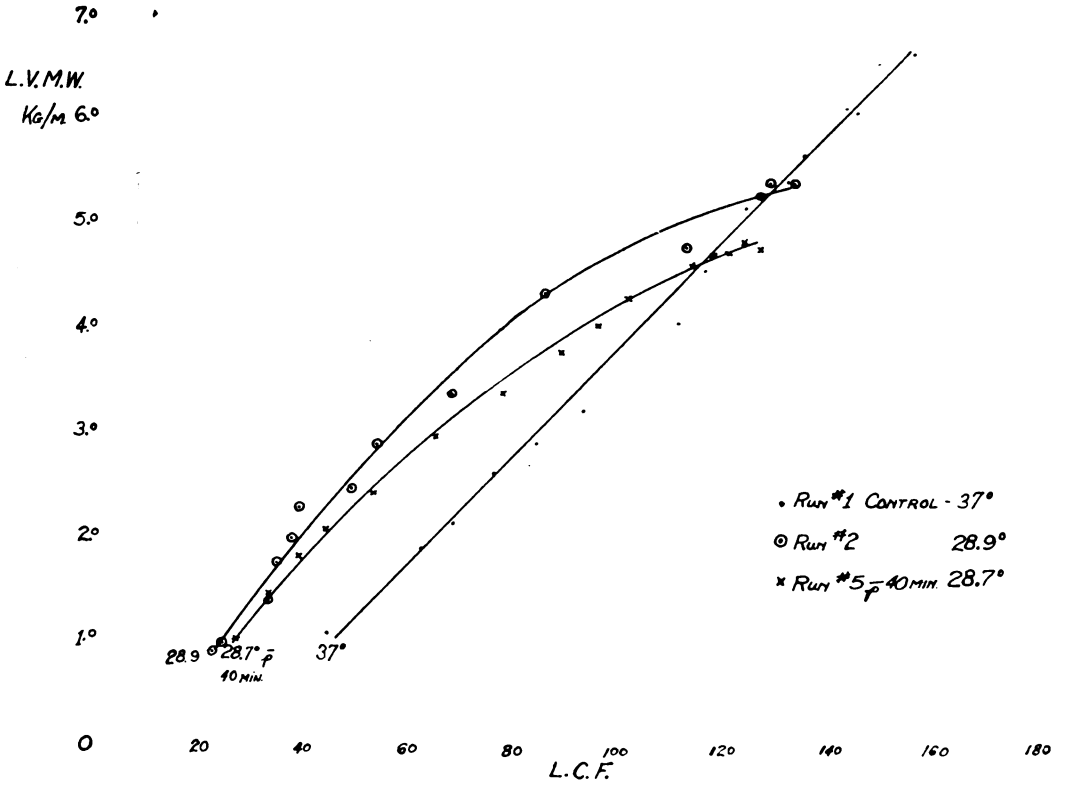

FIG. 5.—Left ventricular minute work (kg.-metres) plotted against left coronary artery flow at (1) 37° C.; (2) 28.9° C.; and (3) 28.7° C. 40 min. after (2).

indicating a smooth and progressive transition of the physiological state over the range of temperature used. The range of temperature studied is essentially that covered in the clinical application of hypothermia.

The relatively greater reduction in coronary flow and its fall to low values might suggest coronary insufficiency. Observation of the simultaneously recorded values of rate and pressure, however, suggests that this fall in coronary flow is due solely to a reduction in myocardial oxygen requirements. It has been shown that the important determining factors of myocardial oxygen consumption are the pressure generated by the ventricle and the heart rate at which it does so (Case, Sarnoff, Braunwald, Stainsby, and Taylor, 1956). The fall in aortic pressure and the heart rate simultaneously may thus account for the large reduction in coronary flow. According to Penrod (1951) there is no fall in oxygen content of the coronary sinus blood during cooling. This would also indicate a sufficient coronary flow.

No rise in filling pressures was observed during cooling to 28° C., although a rise in filling pressures has been previously reported, especially at temperatures below 28° C. (Bigelow, Lindsay, and Greenwood, 1950). In view of the ventricular function data there is no reason to expect a rise in these pressures. Inasmuch as the amount of stroke work per unit of filling pressure is virtually the same at 28° C. and 37° C. atrial pressure should not rise unless necessitated by an increase in stroke work or an increase in heart rate. In Fig. 1, left atrial pressure has actually fallen slightly due to a concomitant fall in stroke work. It follows that any rise in filling pressure during hypothermia is probably due to causes other than cooling.

During cooling, stroke volume did not fall, and hence the observed decrease in cardiac output was due entirely to the diminished heart rate. In the experiment shown in Fig. 1 peripheral resistance fell from 50.8 units to 31.4 units in spite of a falling aortic pressure.

B. VENTRICULAR FUNCTION CURVES.—Curves obtained under hypothermia at spontaneous heart rates were sometimes better than at normal temperatures. This would imply that myocardial contractility may be greater at 28° C. than at 37° C. However, ventricular function curves may be elevated by lowering the heart rate (Berglund and others, to be published), and so in order to equate contractility the experiments were repeated at controlled rates (Fig. 3). This demonstrated that the curves were approximately equal at the two temperatures.

Ventricular function curves may also vary depending on the manner by which the work is increased (Stainsby, Sarnoff, Braunwald, Case, and Welch, 1956). When the rate was kept constant, aortic pressure and cardiac output changes were comparable at both temperatures.

Hence, one may conclude from this experiment (Fig. 3) and from the two others at constant rates with similar results that myocardial contractility at 28° C. is approximately equal to that at 37° C.

Reissmann and Kapoor (1956) found that the "work capacity" of the heart is reduced as the temperature is lowered, using the heart–lung preparation. They plotted "minute" work instead of "stroke" work against filling pressure. The work per minute decreases as the heart rate is lowered at lower temperatures; this does not reflect contractility as they imply. This fall in cardiac output during hypothermia is more than compensated for by the reduction in overall metabolism, as may be seen from narrower A–V differences.

High pulse rates in hypothermia show a severe depression of the ventricular function curve. This type of low curve has been produced by coronary insufficiency, which in this case is probably related to the reduced diastolic period during hypothermia (Hegnauer, Shriber, and Haterius, 1950). Berne (1954) has demonstrated that tachycardia during hypothermia may result in a complete cessation of coronary flow.

Inasmuch as ventricular function curves are obtained in the anaesthetized, open-chested dog, they have been criticized for being far removed from the clinical situation. In this case, the curves are obtained under the same experimental conditions as would apply during actual hypothermic cardiac surgery.

C. CORONARY FLOW.—The adequacy of coronary flow during hypothermia has been questioned and implicated as a cause of ventricular fibrillation (Lange, Weiner, and Gold, 1949). This assumption is not supported by an increased coronary A–V difference in hypothermia, and there is no reason to believe that the low coronary flows present at 28° C. are due to anything other than the reduced oxygen requirements of the heart.

In these experiments it was possible to increase stroke work at 28° C. as much as at 37° C. The presence of coronary insufficiency would have resulted in a severely depressed curve. In response to an increased work load the coronary bed was able to accommodate a sixfold increase in coronary flow, whereas in coronary insufficiency the coronary bed is already maximally dilated.

Fig. 4 shows that at a lower temperature there is less coronary flow for an equivalent amount of work and presumably less oxygen consumption if one assumes no change in coronary A–V differences. This apparent increase in efficiency may not be due to hypothermia alone but to the fall in heart rate and aortic pressure resulting from hypothermia.

SUMMARY AND CONCLUSION

(1) Coronary flow, cardiac output, heart rate, and aortic, pulmonary artery, left atrial, and right atrial pressures were continuously and simultaneously recorded in the dog during cooling.

(2) Ventricular function curves were obtained at 37° C. and 28° C. by intermittent transfusions of blood while recording the above-mentioned variables.

(3) There was no evidence of a rise in right or left mean atrial pressure during cooling.

(4) All other variables fell progressively except stroke volume; coronary flow fell relatively more than aortic pressure and cardiac output.

(5) Peripheral resistance decreased.

(6) Myocardial contractility, i.e., stroke work delivered per unit of filling pressure, was not impaired by the induction of hypothermia.

(7) If the low heart rate normally encountered under hypothermia is artificially elevated, however, contractility is diminished.

(8) An increased efficiency of oxygen utilization during hypothermia is suggested inasmuch as a reduced amount of left main coronary flow per unit of left ventricular minute work occurs in this state.

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