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THE BIOLOGICAL RELATIONS OF THE AORTA AND
CORONARY ARTERIES

by

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THE BIOLOGICAL RELATIONS OF THE AORTA AND
CORONARY ARTERIES

I. PURPOSE OF INVESTIGATION.

Study of the Coronary Arteries.

The coronary arteries are responsible for the blood supply to the heart, and the nutrition of every part of the body depends upon their fulfilling their function adequately. In spite of their great importance however, comparatively little is definitely known about them.

During recent years much work has been carried out on the coronary circulation, mainly along two lines of investigation. On the one hand numerous workers have studied the vascular distribution and the complex anastomoses between the branches of the coronary arteries. On the other hand the coronary flow has been studied in the heart-lung preparation, chiefly by Anrep and his co-workers in this country, and by Smith, Miller, etc. in the U.S.A.

There is, however, no reference in the literature/

literature to any accurate measurement of the coronary arteries. The present research was undertaken to ascertain what relationship, if any, exists between the coronary cross section and the work of the heart, the pulse rate being taken as an indication of the heart work.

Before proceeding to the actual measurements a series of experiments was carried out to find the effects of post mortem changes on the vessels. This was necessary owing to the fact that many of the specimens could not be examined until some time after death, and the accuracy and value of post mortem measurement had to be estimated, and a method evolved to measure the vessels as nearly as possible under their natural conditions during life.

II. /

II. METHOD OF INVESTIGATION

Methods of Measurement.

In order to find a method of obtaining accurate measurements of the coronary arteries the work of previous investigators was reviewed.

The direct measurement of arteries after death by calipers, as performed by Kani (1), is not applicable owing to the coronaries being embedded in the heart muscle from their origin. This method is quite fallacious in any case as no account is taken of the effects of pressure on the arterial capacity, a subject which was studied by Roy (2).

The effect of temperature has also to be taken into consideration as was shown by the work of Cruickshank and Rau (3). This made the injection of solutions of paraffin and gelatin to obtain casts useless, owing to the melting points being at unsuitable temperatures.

The method of obtaining celloidin casts as used by Krassuskaja (4), Huber (5) and Hinman (6) did not give accurate enough results owing/

owing to the contraction of the vessels when the casts set.

Several workers have injected opaque materials and used X-ray examination. Although useful for studying arterial distribution the methods of such workers as Crainicianu (7) and Pace (8) are not compatible with true measurement owing to the action of the injected materials on the arterial wall. The injection of lipiodol, as carried out by Roussac (9), was examined for possible fallacies. Nagaoka (10) used lipiodol for the radiological study of the blood vessels of the kidney. He found the method unsatisfactory owing to the impossibility of any subsequent pathological sectioning. This objection, however, does not hold in the present investigation. The effect of lipiodol was tried on the cat's carotid. The diameter of the carotid was measured with calipers in the anaesthetised cat, and then the artery was excised and filled with lipiodol at a temperature of 37°C. One end of the vessel was tied off and the other joined up to a pressure of 100 mm. of mercury and the diameter measured again. This was tried in several animals and the readings obtained from the/

the vessels in situ and after filling with lipiodol were found not to differ more than 5 per cent.

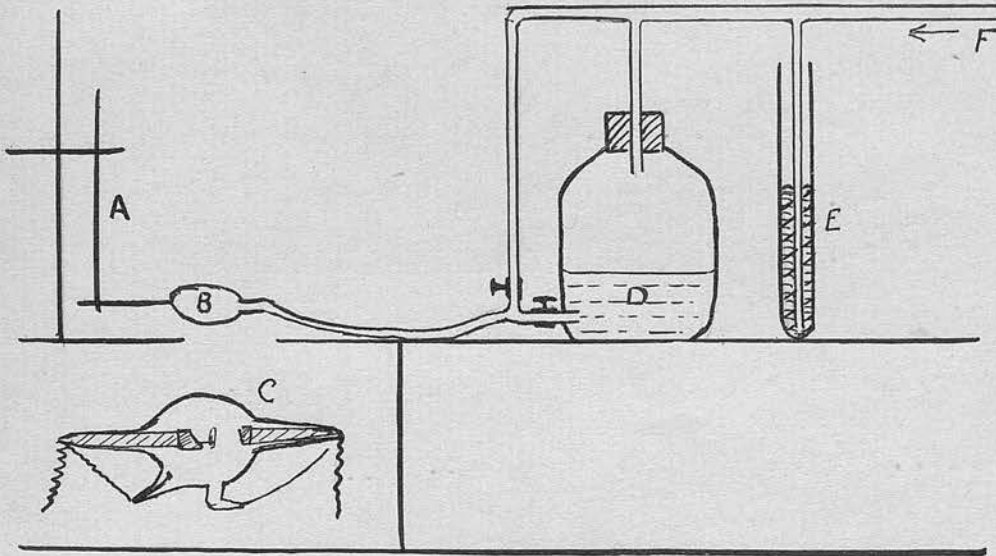
The injection of lipiodol appears to be free from any serious error. Lipiodol is inert and does not affect the arterial wall, temperature and pressure can be adjusted to normal and there is no handling and consequent traumatism of the actual arteries examined.

Method of Injection.

A simple apparatus was fitted up as shown in Fig. 1.

Fig. 1./

Fig. 1.



A - Clamp

B - Heart

C - X-ray tube

D - Ringer

E - Pressure valve

F - O₂ supply

This allowed Ringer, oxygen or lipiodol to be driven through the coronaries at any pressure desired, which could be obtained by adjusting the graduated mercury pressure valve. This method proved to be quite satisfactory in most cases but occasionally the aortic valves proved incompetent and this resulted in the filling of the ventricle with lipiodol.

The technique varied slightly in different cases but was always similar. The hearts were removed from the body either as soon as possible after death, or when possible whilst the animals were still under anaesthesia; the last method was employed in the preliminary experiments.

After the removal of the pericardium the heart was emptied of blood and washed in Ringer and a cannula was tied into the aorta in the case of the smaller animals. In the larger animals, such as sheep or bullock, the aorta was cut open and the cannulae tied into the coronary orifices by purse string ligatures. The heart was then held in a special adjustable clamp to allow of rotation, and pins of known diameter were inserted into the heart muscle. The pins were placed one between coronaries and tube and one between/

between coronaries and plate so as to bracket the vessels. The heart was then immersed in Ringer at 37°C. and Ringer at 37°C. was passed through at a pressure equal to the normal blood pressure of the animal in question. After a few minutes when the vessels were thoroughly washed out the Ringer was cut off and oxygen was driven through to blow out the Ringer. The pressure was then cut off and lipiodol was injected into the cannula at a temperature of 37°C. The amount of lipiodol required depended on the size of the heart. The pressure was then turned on at 50 mm. of mercury and the heart screened. Whilst being screened the clamp was adjusted until both coronaries were shown at their origin from the aorta. It was found that to get clear definition of the vessels in the photograph the heart had to be at a distance of about 30 inches from the tube. The heart was screened and adjusted near the tube for clearness in screening and then the clamp was moved to get the heart 30 inches away from the tube. A radiograph was taken and the pressure then increased to 100 mm. mercury or the normal systolic pressure of the animal examined and then a second picture taken. Finally/

Finally the pressure was cut off, the tubing opened and a picture was taken at zero pressure.

In the experiments made to determine the effects of temperature one exposure was taken at 37° C. and then the heart was cooled down to room temperature of 20° C. and a second photograph taken.

Post mortem contraction was measured by first taking a radiograph of the fresh heart at 100 mm. of mercury. The pressure was then cut off and the heart left for twenty-four hours. Pressure was then put on again and a second radiograph taken.

For the actual measurement of the vessels prints were developed from the negatives. The measuring was done with a reading microscope with graduated scale reading to 0.02 mm. The diameter of the pins was measured and the magnification of the print estimated and the measurements of the arteries corrected to obtain their natural size.

In all cases the vessels were measured at their origin from the aorta and their cross-section worked out. The aorta was measured just distal to the origin of the coronaries. The aortic cross-section in the case of the rat, rabbit/

rabbit, and cat was measured from the X-ray photographs. In order to measure the aorta in the larger animals a piece of aorta was taken, one end was closed by a cork and the other end was attached to the oxygen supply. The outside diameter was measured by calipers and the total cross-section obtained. The actual internal cross-section was got by subtraction of the area of thickness of the aortic wall.

III. /

III. EXPERIMENTAL ERRORS

Errors in measurement could arise from three sources, all of which were investigated. These were the effects of pressure, temperature and post mortem contraction.

Effects of Pressure.

The cross-sections of the aorta and coronaries were worked out at pressures of 0 mm., 50 mm, and 100 mm. mercury in a series of animals, both in the fresh hearts and in post mortem specimens.

It was found that the increase of cross-section varied with increase of pressure in a different manner in these two types of specimen. In the fresh specimen the increase in cross-section on raising the pressure from 0 mm. to 50 mm. was greater than the increase on raising pressure from 50 mm. to 100 mm. This was found to hold both for the aorta and the coronaries. This result is in agreement with the experiments of MacWilliam (11) who worked on relaxed and contracted /

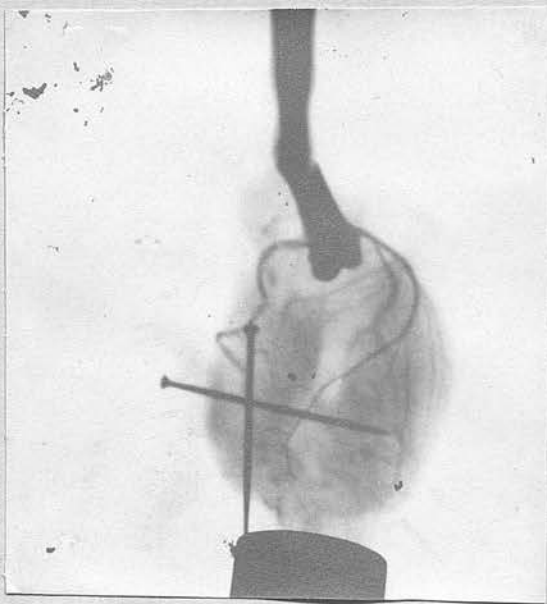
contracted arteries.

In the specimens showing post mortem contraction the effect of pressure was quite different.

Radiographs of Cat's Aorta and Coronaries under increasing pressure.

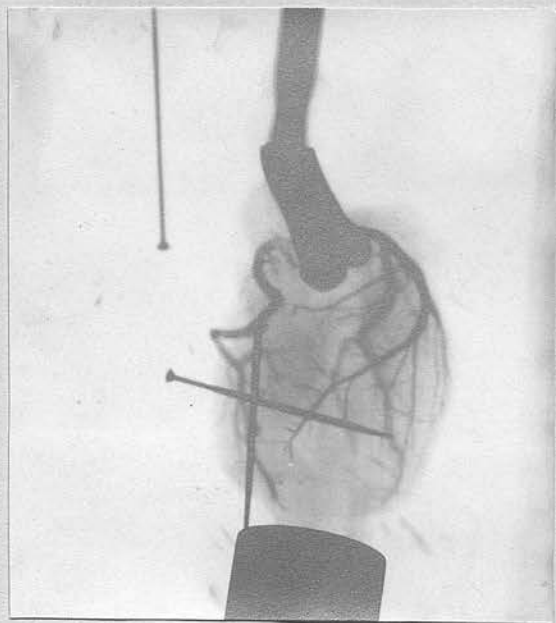
Cat 24 hours specimen.

No. 1. Pressure 0 mm.

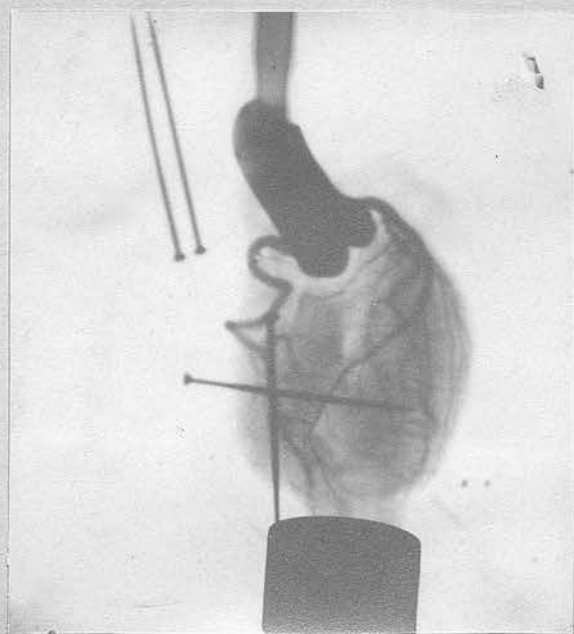


No. 2/

No. 2. Pressure 50 mm.



No. 3. Pressure 100 mm.



In these specimens the greater increase in cross section is seen on raising the pressure from 50 mm. to 100 mm. mercury. This agrees with the experiments of Roy (2), who laid down the law that the maximum distensibility of arteries is at a point corresponding with the normal blood pressure for the animal in question. MacWilliam pointed out that this statement of Roy's was due to the fact that all his experiments were carried out on contracted arteries.

These results are shown in Table I and Fig. 2 for aortic cross section, and in Table II and Fig. 3 for coronary cross section.

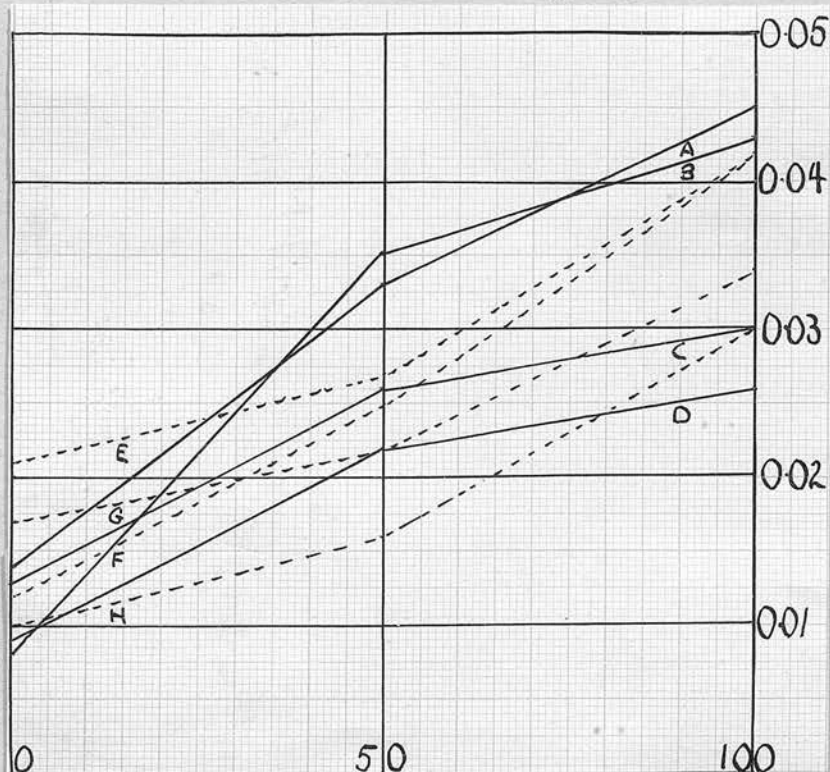
Table I.

Aortic Cross section in sq.cm.

| | | Fresh Heart | | | Heart 24 hours after death | | | | |
|-----|--------|---------------------|------|------|----------------------------|--------|---------------------|------|------|
| No. | Animal | Pressure in mm. Hg. | | | No. | Animal | Pressure in mm. Hg. | | |
| | | 0 | 50 | 100 | | | 0 | 50 | 100 |
| A | Cat | .145 | .553 | .636 | E | Cat | .176 | .283 | .453 |
| B | Monkey | .233 | .377 | .484 | F | Cat | .141 | .286 | .478 |
| C | Rabbit | .082 | .377 | .534 | G | Cat | .154 | .220 | .478 |
| D | Cat | .220 | .302 | .346 | H | Rabbit | .101 | .233 | .377 |

Fig. 2.

Aortic cross section in sq.cm.



Abscissa - Pressure in mm. of mercury
 Ordinate - Aortic cross section in sq.cm.

Table II.

Coronary Cross section in sq.cm.

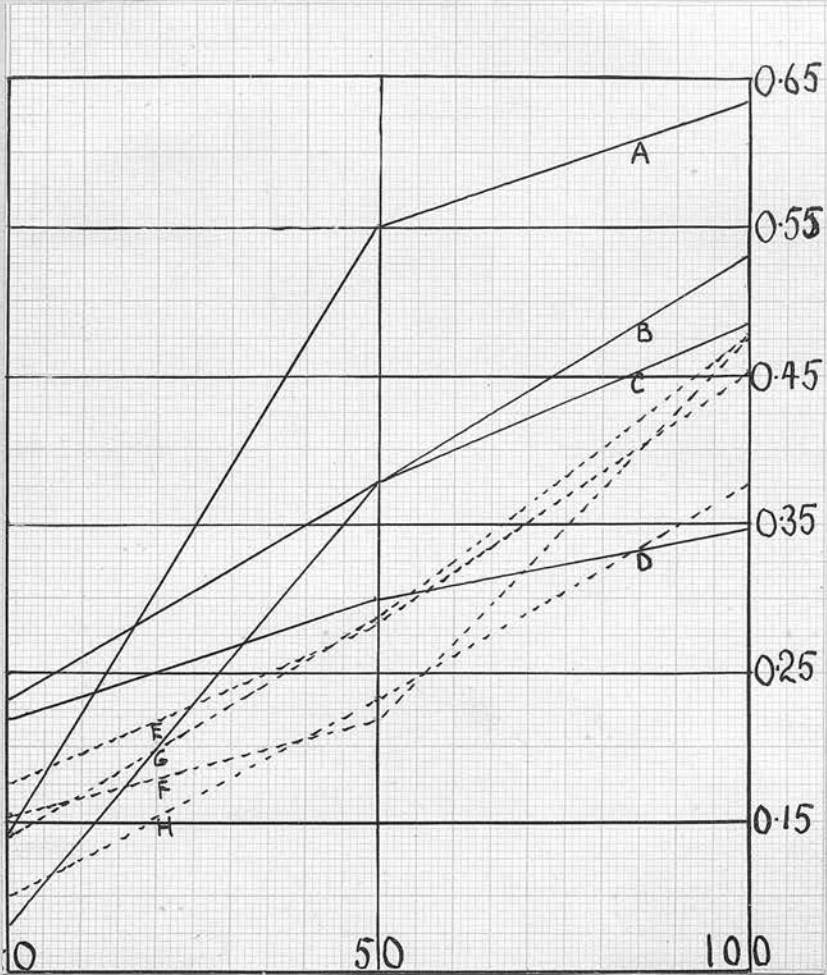
| Fresh Heart | | | | | Heart 24 hours after death. | | | | |
|-------------|--------|---------------------|------|------|-----------------------------|--------|---------------------|------|------|
| No. | Animal | Pressure in mm. Hg. | | | No. | Animal | Pressure in mm. Hg. | | |
| | | 0 | 50 | 100 | | | 0 | 50 | 100 |
| A | Cat | .014 | .033 | .045 | E | Cat | .021 | .027 | .042 |
| B | Monkey | .008 | .035 | .043 | F | Cat | .012 | .025 | .042 |
| C | Cat | .013 | .026 | .030 | G | Cat | .017 | .022 | .034 |
| D | Rabbit | .009 | .022 | .026 | H | Rabbit | .010 | .016 | .030 |

Fig. 3.

Coronary cross section in sq.cm.

Fig. 3. /

Fig. 3.



Abscissa - Pressure in mm. of mercury

Ordinate - Coronary cross section in sq.cm.

Effects of Temperature.

The cross sections of the aorta and coronaries were worked out both at room temperature of 20°C. and at the body temperature of 37°C. The effect of temperature was found to be different in the cases of the aorta and the coronaries. The coronaries when cooled from 37°C. to 20°C. relaxed and their cross-section increased. When the aorta was cooled down however it contracted with a consequent decrease in cross section. The percentage change was worked out in five cats and the results are shown in Table III.

Table III.

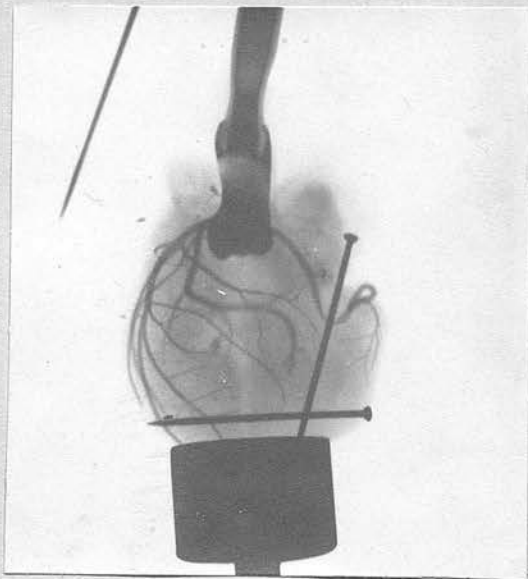
Aortic and Coronary Cross section in sq.cm. at pressure of 100 mm. Hg. and temperature of 20°C. and 37°C.

| Animal | Aortic cross section | | % Diff- erence | Coronary cross section in sq. cm. | | % Difference |
|--------|----------------------|---------|-------------------|---|-------|--------------|
| | 20°C. | 37°C. | | 20°C. | 39°C. | |
| Cat | .402 | .424 | 5 | .036 | .031 | 14 |
| Cat | .217 | .226 | 4 | .022 | .020 | 10 |
| Cat | .390 | .409 | 5 | .033 | .029 | 12 |
| Cat | .283 | .302 | 6 | .031 | .029 | 7 |
| Cat | .149 | .157 | 5 | .015 | .014 | 7 |
| | | Average | 5 | | | 10 |

This effect of temperature on the aorta and coronaries was shown by Cruickshank and Rau (3), who carried out experiments on fresh excised coronary and systemic arteries.

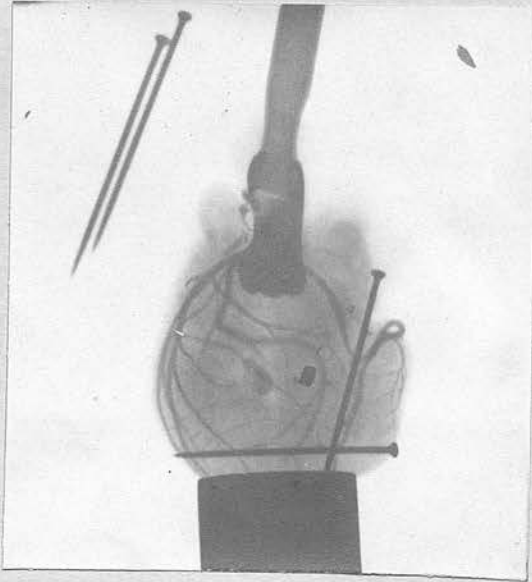
Radiographs of Cat's Aorta and Coronaries at different Temperatures.

No. 1. Temperature 37°C.



No. 2/

No. 2. Temperature 20°C.



Effects of Post mortem Contraction.

To estimate the contraction of the vessels after death, hearts were radiographed fresh and again after twenty-four hours. On working out the cross sections it was found that both the aorta and coronaries showed contraction. The following table shows the percentage contraction as worked out on five cats.

Table IV. /

Table IV.

Aortic and Coronary Cross section in sq.cm. in fresh and 24 hours old hearts.

| Cat | Aortic cross section | % Difference | Coronary cross section | % Difference |
|----------------|----------------------|--------------|------------------------|--------------|
| fresh | .226 | | .017 | |
| 24 hrs | .217 | 4 | .016 | 6 |
| fresh | .377 | | .025 | |
| 24 hrs | .268 | 3 | .022 | 12 |
| fresh | .503 | | .042 | |
| 24 hrs | .465 | 8 | .038 | 10 |
| fresh | .346 | | .039 | |
| 24 hrs | .321 | 3 | .035 | 10 |
| fresh | .327 | | .039 | |
| 24 hrs | .299 | 9 | .036 | 8 |
| <u>Average</u> | | 6.4 | | 9.2 |

These figures show that post mortem contraction causes a contraction in the coronaries of roughly 9.2 per cent, and that cooling to room temperature causes a relaxation of roughly 10 per cent. in the coronaries. Therefore examination of the post mortem specimen at 20°C. should give an/

an approximately accurate measurement of the coronary cross section, and consequently post mortem specimens can be used when fresh specimens are not available.

Examination of Specimen more than twenty-four hours after death.

It has been shown that the error due to post mortem contraction in the specimen examined twenty-four hours after death may be compensated for by alteration of temperature. If, however, the specimen is several days old the degree of contraction is too great for any useful measurement. This is shown in the accompanying figures of measurement of the coronary cross section in the normal healthy human heart in sq.cm.

| | |
|---|--------------|
| Average coronary cross section per gm. heart weight (24 hours specimen) | _____ 0.0011 |
| Coronary cross section per gm. heart weight in 4 days old specimen | _____ 0.0007 |
| Coronary cross section per gm. heart weight in 5 days old specimen | _____ 0.0006 |

All examinations of the post mortem specimen were accordingly made within twenty-four hours of death to obtain accurate results.

IV. RESULTS.

The following tables give the results of the measurements of aortic and coronary cross section. The figures were obtained by measurement of the fresh heart at temperature of 37°C. or of the heart twenty-four hours after death at temperature of 20°C. In each case the measurements are at a pressure which is approximately the same as normal systolic pressure of the animal examined.

Table V. /

Table V.

Cat - Aortic and Coronary cross section in sq.cm.

| Wt. in grams | | Heart ratio. $\frac{HW \times 100}{BW}$ | Coronary cross section | Coronary cross sect. per Gm. heart wt. | Aortic cross section | Aortic cross section per Gm. body wt |
|--------------|-----------|--|------------------------|--|----------------------|--------------------------------------|
| Body wt. | Heart wt. | | | | | |
| 2600 | 13 | .50 | .036 | .0028 | | |
| 3400 | 16 | .47 | .036 | .0023 | | |
| 3310 | 17 | .53 | .051 | .0030 | .478 | .00014 |
| 4180 | 20.5 | .49 | .045 | .0022 | | |
| 2980 | 14 | .47 | .038 | .0027 | | |
| 2830 | 13 | .46 | .017 | .0013 | | |
| 4270 | 17.5 | .41 | .040 | .0023 | | |
| 3300 | 15.5 | .47 | .042 | .0027 | .503 | .00015 |
| 3020 | 13 | .43 | .039 | .0030 | | |
| 2700 | 13.5 | .50 | .031 | .0023 | .424 | .00015 |
| 3900 | 16 | .41 | .029 | .0018 | | |
| 2720 | 12.5 | .46 | .029 | .0023 | .377 | .00014 |
| 2500 | 12.5 | .50 | .024 | .0019 | | |
| 2180 | 12 | .55 | .021 | .0018 | | |
| 2170 | 11.5 | .53 | .042 | .0037 | .327 | .00015 |
| 2040 | 10 | .49 | .027 | .0027 | | |
| 2350 | 12 | .51 | .026 | .0022 | | |
| 2400 | 11.5 | .48 | .040 | .0035 | .302 | .00013 |
| 1765 | 9 | .51 | .036 | .0040 | | |
| 2840/ | | | | | | |

Table V. contd.

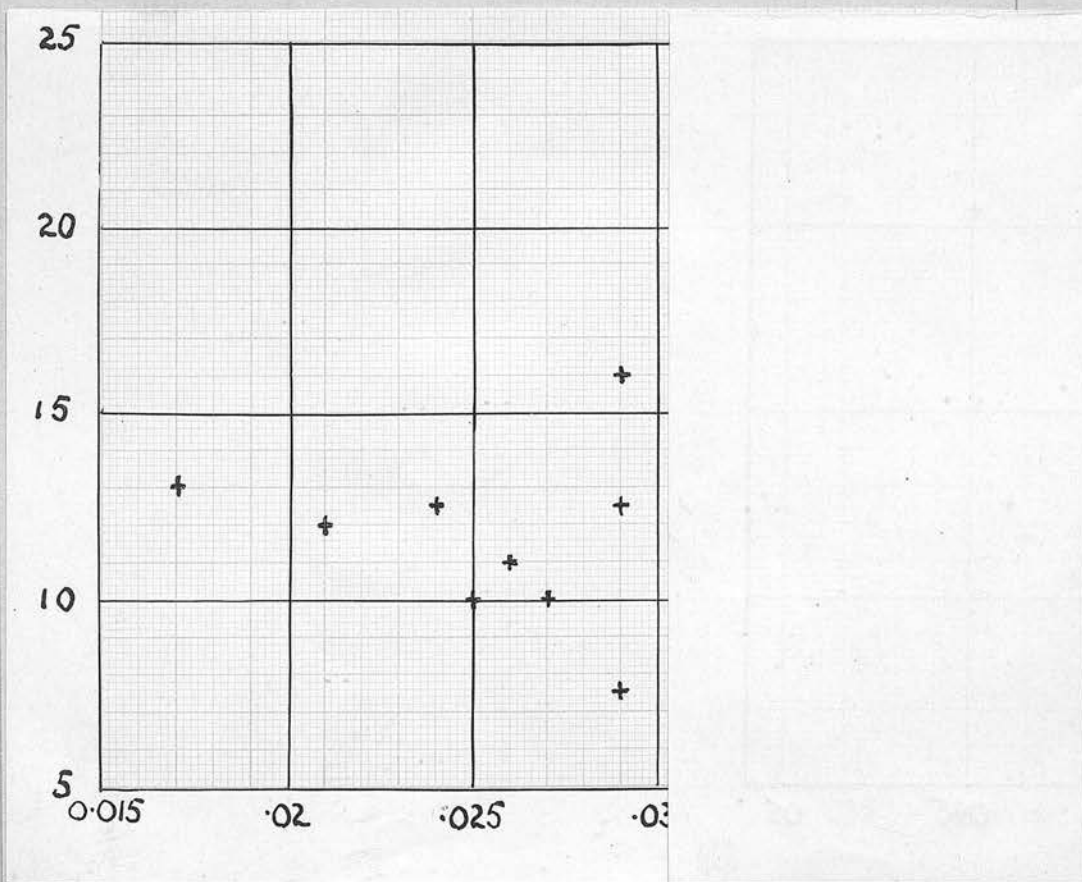
| Wt. in grams | | Heart ratio $\frac{HW \times 100}{BW}$ | Coronary cross section | Coronary cross sect.per Gm.heart wt. | Aortic cross section | Aortic cross section per Gm. body wt. |
|--------------|-----------|--|------------------------------|--|----------------------------|---|
| Body wt. | Heart wt. | | | | | |
| 2840 | 12.5 | .44 | .044 | .0035 | .409 | .00014 |
| 1890 | 10 | .53 | .025 | .0025 | | |
| 2680 | 11 | .41 | .034 | .0031 | .377 | .00014 |
| 2820 | 11 | .39 | .039 | .0027 | . | |
| 2000 | 9 | .45 | .039 | .0043 | | |
| 1890 | 7.5 | .44 | .029 | .0039 | | |
| 1440 | 6.5 | .45 | .014 | .0022 | .266 | .00016 |

These figures for heart weight and coronary cross section show such wide variations in the cat that they may be plotted on graph paper to show if there is any relationship between them.

Fig. 4. /

Fig. 4.

Cats. Ordinate - heart weight in grams
Abscissa - coronary cross section in sq. cm.



From/

From Fig. 4 it can be seen that there is very little correlation between coronary cross section and heart weight in cats. The size of the cross section of the coronary arteries is but little influenced by the size of the heart. This is shown in the following table.

Table VI.

| | Heart weight less than 13 grams | Heart weight 13 grams or more. |
|--|---------------------------------|--------------------------------|
| No. of experiments _____ | 15 | 11 |
| Average heart weight in grams _____ | 10.6 | 15.4 |
| Average coronary cross section in sq.cm. _____ | 0.033 | 0.037 |

The average figures for cat may be taken as follows.

| Body wt. in Gm. | Heart wt. in gms. | Heart Ratio $\frac{HW \times 100}{B.W.}$ | Coronary cross section in sq.cm. | C.C.S. per gm. Ht. wt. | Aortic C.S. in sq. cm. | A.C.S. per Gm. B.W. |
|-----------------|-------------------|--|----------------------------------|------------------------|------------------------|---------------------|
| 2700 | 12.6 | 0.47 | .034 | .0027 | .390 | .00015 |

The results of the measurement of coronary and aortic cross section in the other animals are contained in the following table.

Table VII /

Table VII.

| Animal | Weight in grams | | Heart ratio. $\frac{HW \times 100}{BW}$ | Coronary cross section in sq. cm. | C.C.S. per Gm. heart wt. (sq. cm.) | Aortic cross section in sq. cm. | A.C.S. per Gm. body weight (sq. cm.) |
|--------------------|-----------------|--------------|---|---|---|--|--|
| | Body wt. | Heart wt. | | | | | |
| Rat | 238 | 1.00 | 0.42 | .0032 | .0032 | 0.126 | .00053 |
| | 182 | 0.80 | 0.44 | .0034 | .0043 | 0.070 | .00038 |
| | 205 | 0.85 | 0.41 | .0036 | .0040 | 0.092 | .00045 |
| | 225 | 0.90 | 0.40 | .0032 | .0035 | 0.090 | .00040 |
| Averages | 212 | 0.90 | 0.42 | .0033 | .0037 | 0.095 | .00044 |
| Rabbit | 2480 | 6.7 | 0.27 | .021 | .0031 | .441 | .00018 |
| | 2300 | 6.0 | 0.26 | .018 | .0030 | .377 | .00016 |
| | 2590 | 7.0 | 0.27 | .020 | .0029 | .420 | .00016 |
| | 2660 | 8.0 | 0.30 | .019 | .0024 | - | - |
| | 1960 | 5.5 | 0.28 | .016 | .0029 | .350 | .00018 |
| Rabbit averages | 2400 | 6.6 | 0.28 | .019 | .0029 | .397 | .00017 |
| Sheep | 39,100 | 180 | | 0.185 | .0010 | - | - |
| | 47,800 | 220 | 0.46 | 0.252 | .0011 | 5.30 | .00011 |
| | 41,300 | 190 | | 0.189 | .0010 | 4.72 | .00011 |
| Sheep averages | 42,800 | 197 | | 0.209 | .0010 | 5.01 | .00011 |
| Ox | 733,000 | 3300 | | 1.641 | .0005 | - | - |
| | 644,000 | 2900 | | 1.160 | .0004 | 38.64 | .00006 |
| | 444,000 | 2000 | 0.45 | 0.636 | .0003 | 27.20 | .00006 |
| Ox averages | 607,000 | 2700 | | 1.146 | .0004 | 32.92 | .00006 |
| Horse | 750,000 | 4800 | | 3.450 | .0007 | 54.20 | .00007 |
| | 500,000 | 3200 | | 1.930 | .0006 | 34.80 | .00007 |
| | 470,000 | 3000 | 0.64 | 1.720 | .0006 | - | - |
| | 695,000 | 4450 | | 2.702 | .0006 | - | - |
| Horse averages | 604,000 | 3850 | | 2.450 | .0006 | 44.50 | .00007 |
| Normal/ | | | | | | | |

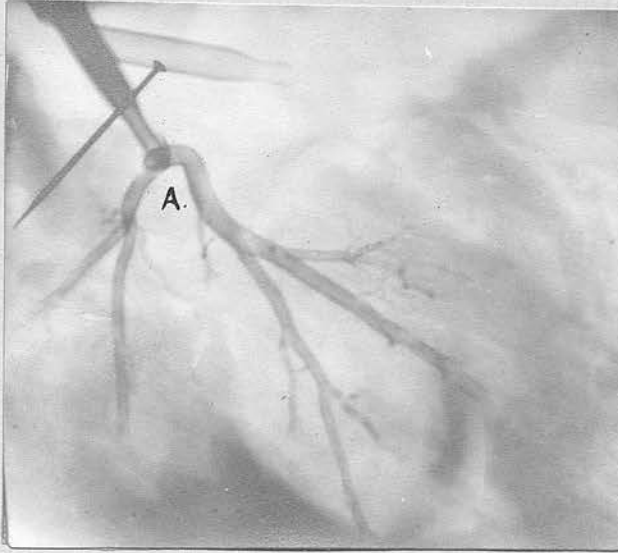
Table VII. contd.

| Animal | Weight in grams | | Heart ratio $\frac{HW \times 100}{BW}$ | Coronary cross section in sq. cm. | C.C.S. per Gm. heart wt. (sq. cm.) | Aortic cross section in sq. cm. | A.C.S. per Gm. body weight (sq. cm.) |
|---------------|-----------------|-----------|---|-----------------------------------|------------------------------------|---------------------------------|--------------------------------------|
| | Body wt. | Heart wt. | | | | | |
| Normal human | 70,000 | 350 | | 0.384 | .0011 | 7.82 | .00011 |
| (child) | 23,000 | 115 | | 0.131 | .0011 | - | - |
| | 58,000 | 290 | | 0.264 | .0009 | - | - |
| | 48,000 | 240 | 0.50 | 0.242 | .0010 | 5.09 | .00011 |
| | 52,000 | 260 | | 0.298 | .0011 | - | - |
| | 50,000 | 250 | | 0.269 | .0011 | 5.38 | .00011 |
| Human average | 56,000 | 280 | | 0.291 | .0011 | 6.10 | .00011 |

Radiographs /

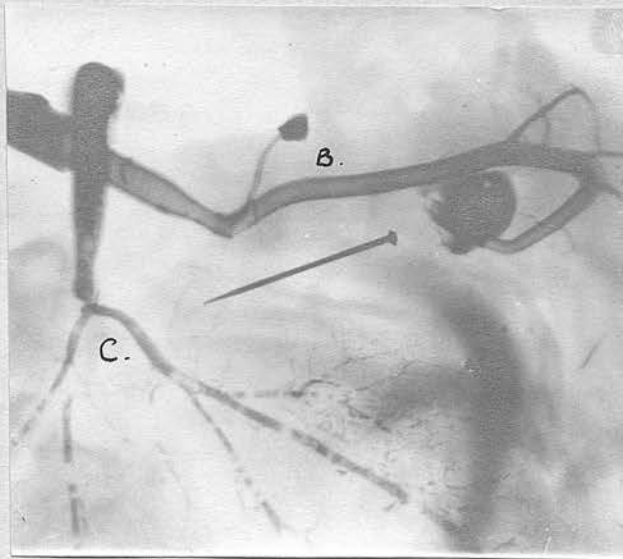
Radiographs of coronary arteries of man.

No. 1.



A - left coronary.

No. 2.



B - right coronary
C - left coronary. C is the same vessel as A
in No. 1, but with the pressure taken
off and shows the effect of pressure on
the vessels.

V. DISCUSSION

The average results obtained for this series of animals are shown in Table VIII, together with various other figures from different sources.

Table VIII.

| Animal | Rat | Rabbit | Cat | Sheep | Man | Horse | Ox |
|---|-------------|-------------|-------------|---------------|---------------|---------------|----------------|
| Body wt. } in gms. } | 212 | 2,400 | 2,700 | 42,800 | 56,000 | 604,000 | 607,000 |
| Heart wt. } in gms. } | 0.9 | 6.6 | 12,6 | 197 | 280 | 3,850 | 2,700 |
| Heart ratio } ($\frac{H \times 100}{B W}$) } | 0.42 | 0.28 | 0.47 | (12) 0.46 | (12) 0.50 | (12) 0.64 | (12) 0.45 |
| Coron- } ary cross } section } in sq.cm. } | 0.0033 | 0.019 | 0.034 | 0.209 | 0.29 | 2.45 | 1.15 |
| C.C.S. per } heart wt. } in sq.cm. } | 0.0037 | 0.0029 | 0.0027 | 0.0010 | 0.0011 | 0.0006 | 0.0004 |
| Aortic } cross } section } in sq.cm. } | 0.095 | 0.39 | 0.39 | 5.01 | 6.10 | 44.5 | 32.9 |
| A.C.S. per } kilo body } wt. in sq. } cm. } | 0.4 | 0.17 | 0.15 | 0.11 | 0.11 | 0.07 | 0.06 |
| Pulse } rate } | (13) 420 | (14) 205 | 160 | (15) 75 | 72 | (15) 36 | (16) 43 |
| Basal } Metabol- } ism (cal- } ories } per diem } | (17) 481 | (18) 148 | (19) 213 | (20) 1,156 | (21) 1,400 | (22) 9,060 | (16) 14,570 |

This series of animals gives a 2,850 fold range of body weight.

Table VIII shows that ^{the} aortic cross section per unit body weight and ^{the} coronary cross section per unit heart weight are much smaller in the larger animals. The reason is that the basal metabolism of animals varies as $(\text{body weight})^{\frac{2}{3}}$ (Rubner⁽¹⁸⁾). Hence the basal metabolic rate

(i.e. $\frac{\text{basal metabolism}}{\text{body weight}}$) varies as $\frac{(\text{body weight})^{\frac{2}{3}}}{\text{body weight}}$

that is as $\frac{1}{(\text{body weight})^{\frac{1}{3}}}$. The supply of oxygen to the tissues is the most important function of the circulation and hence the minute volume of the circulation ^{per unit of body weight} varies as $\frac{1}{(\text{body weight})^{\frac{1}{3}}}$.

of the circulation.

Inspection of Table VIII shows that the aortic cross section and coronary cross section vary in a manner somewhat similar to the basal metabolic rate.

The velocity of the blood flow = $\frac{\text{volume of blood}}{\text{cross section of artery}}$

and hence if the minute volume and the arterial cross section vary in the same manner, the velocity of blood flow will be constant. The exact relation between/

between these factors can be seen best by means of graphs.

Relation of Aortic Cross section to Body Weight

This is shown in Fig. 5. The relation obtained is:

$$\text{Log aortic cross section in sq.cm.} = 0.827 \times (\text{log B.W.} - 3.84)$$

$$\text{or aortic cross section in sq.cm.} = \left(\frac{\text{Body Weight in Gm.}}{6,920} \right)^{0.827}$$

$$\text{or aortic cross section } \propto (\text{body weight})^{0.827}$$

Dreyer, Ray and Walker (23) found the following relation:

$$\text{Aortic cross section in sq.cm. } \propto (\text{body weight})^{0.71}$$

Clark (24) found that

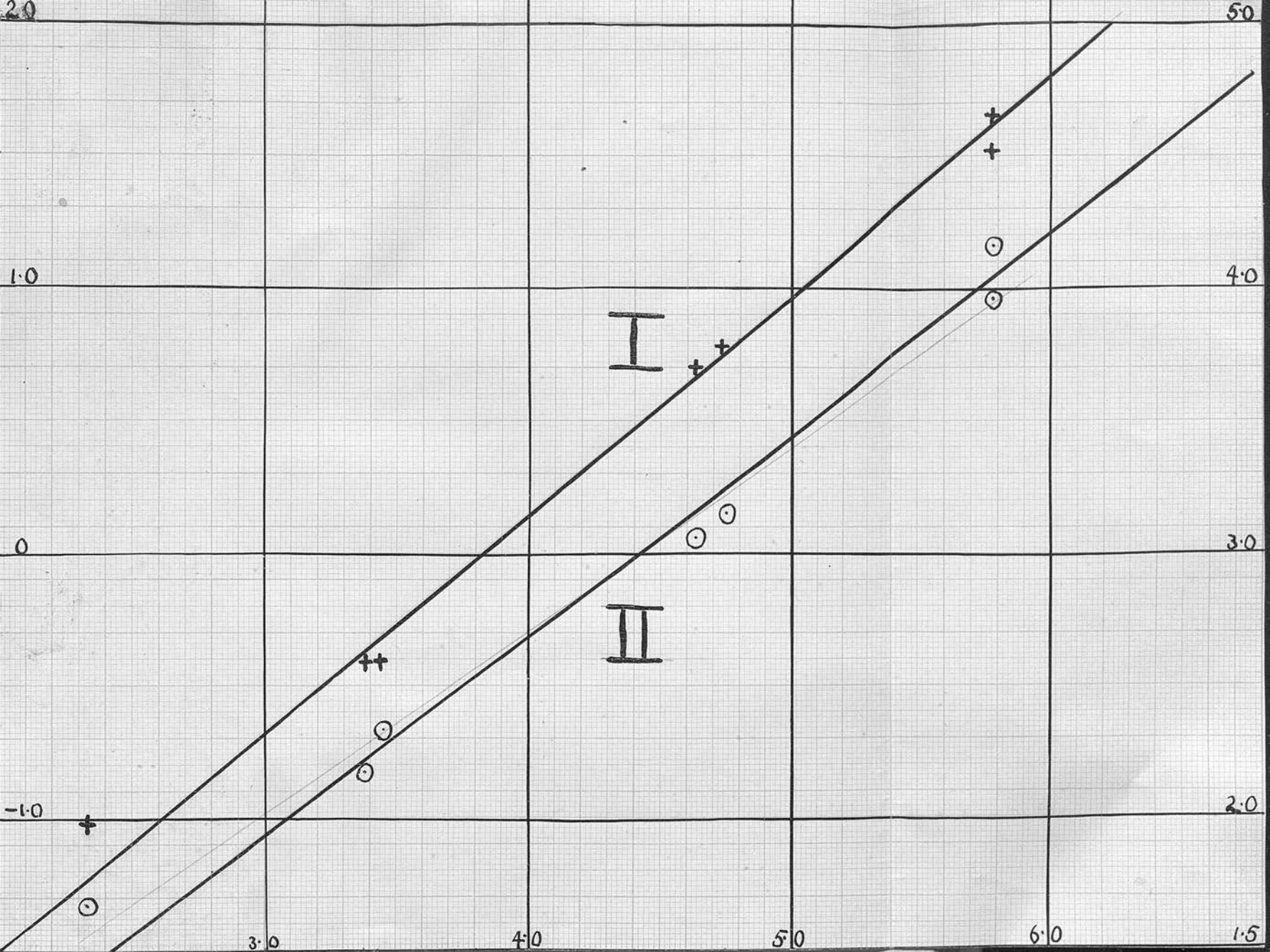
$$\text{aortic cross section in sq.cm. } \propto (\text{heart weight})^{0.8}$$

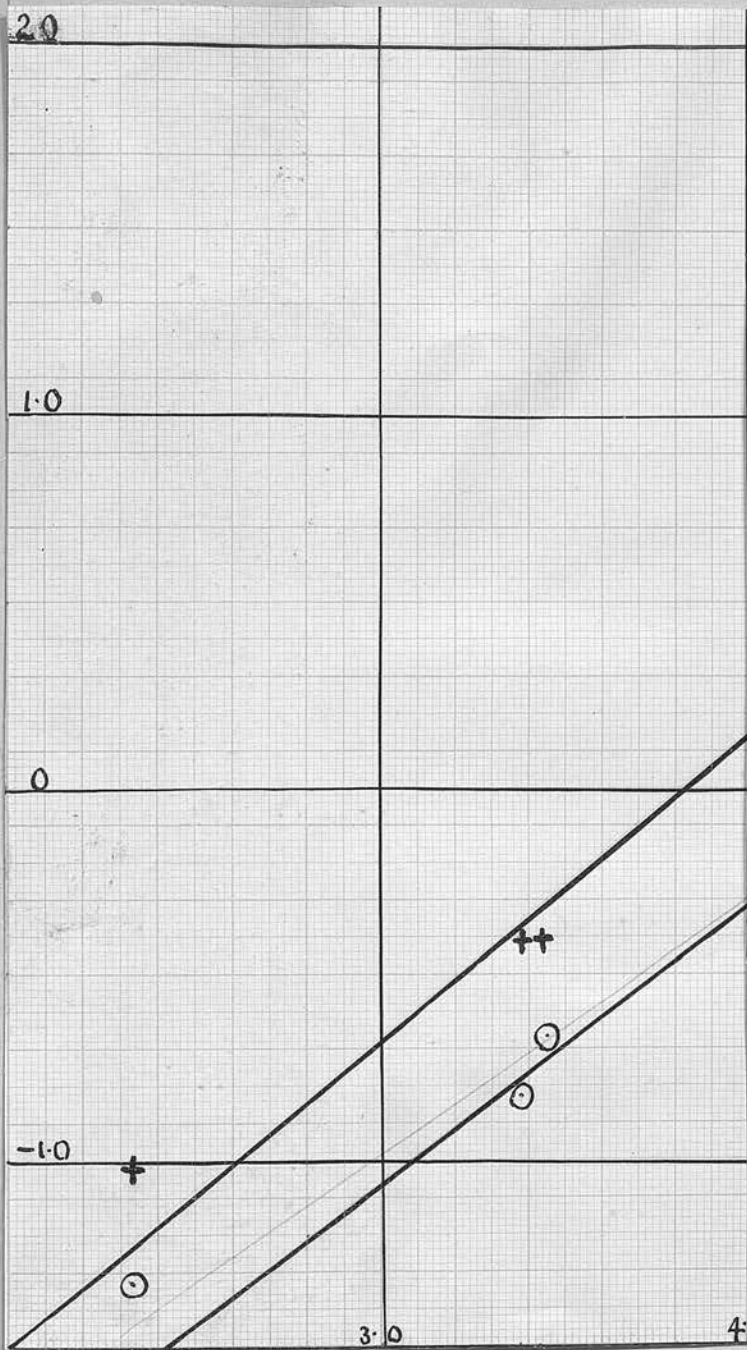
$$\text{and heart weight } \propto (\text{body weight})^{0.9} \quad \text{and hence}$$

$$\text{concluded that aortic cross section } \propto (\text{body weight})^{0.72}$$

These observers, however, measured the aortae under zero pressure. This produces a greater experimental error in the small animals than in the large.

Relation/





Abscissa - log Body Weight in Gms.
 Ordinates - Left, log aortic cross section in sq.cms.
 Right, log calories per diem.

$$I - \text{Aortic cross section in sq.cm.} = \left(\frac{\text{Body Weight in Gms.}}{6,920} \right)^{0.827}$$

$$II - \text{Calories per diem} = \left(\frac{\text{Body Weight in Gms.}}{4.56} \right)^{0.79}$$

$$ACC = \frac{(BW)^{0.82}}{1320}$$

$$Cals = \frac{(BW)^{0.70}}{244.2}$$

Relation of Basal Metabolism to Body Weight.

Fig. 5 also shows the relation between basal metabolism (calories per diem) and body weight. The formula that fits this curve is
log calories per diem = 0.79 x (log body weight - 0.659)
or calories per diem = $\left(\frac{\text{body weight in Gms.}}{4.56}\right)^{0.79}$

This relation between metabolism and body weight in the animals under discussion

$$\text{calories per diem} \propto (\text{body weight})^{0.79}$$

does not agree with the view that the metabolism varies as the body surface, for this gives the relation

$$\text{metabolism} \propto (\text{body weight})^{0.66}$$

The question as to the significance of this latter formula is not clear, and therefore it is unnecessary to discuss the divergence of results.

The essential fact shown by these two sets of figures is that in the animals measured the relation between aortic cross section and body weight is very similar to the relation between basal metabolism and body weight.

If the minute volume of the circulation is proportional to the basal metabolism, this similarity/

similarity means that the velocity of the blood in the aorta will be very similar in animals varying in size from rat to horse.

The velocity of the blood stream in the aorta can be calculated as follows.

A horse of 604 kilos has a basal metabolic rate of 15 calories per kilo per diem. One litre of oxygen supplies 5 calories (on a carbohydrate diet), hence the horse consumes $\frac{604 \times 15}{5}$ litres of oxygen per diem. If the rate of oxygen

utilisation is 5 c.c. per 100 c.c. of blood, this implies a circulation volume of blood per diem of

$$\frac{604 \times 15}{5} \times 1000 \times \frac{100}{5} \text{ c.c.}$$

or

$$\frac{1812 \times 1000 \times 20}{24 \times 60 \times 60} \text{ c.c. blood per sec.} = 419 \text{ c.c.}$$

The aortic cross section is 44.5 sq.cm. and this gives a velocity of $\frac{419}{44.5}$ cm. per second. The

duration of systole in the horse is about 25 per cent. of the cardiac cycle and hence the velocity of blood in the aorta during systole is $\frac{4 \times 419}{44.5}$

= 37.7 cm. per second.

Table/

Table IX gives the calculated velocity of the blood in the aorta during systole for the whole series of animals whose aortic cross section was measured. (The duration of systole was taken as 25 per cent. of the cardiac cycle in the horse and 40 per cent. in the rat, and intermediate figures were taken for animals intermediate in size).

Table IX.

| Animal | Velocity of Blood in Aorta during systole in cm. per second | | Velocity of blood in carotid in cm. per second. |
|--------|---|---------------------|---|
| | Calculated from author's figures | Calculated by Clark | Direct measurement |
| Rat | 78.6 | 255 | |
| Rabbit | 43.5 | 184 | 34 |
| Cat | 72.5 | - | |
| Sheep | 35.7 | 108 | 35 |
| Man | 33.1 | 71 | |
| Horse | 37.7 | 76 | 43 |
| Ox | 82.0 | 170 | |

X reference

Clark (25) calculated these figures and obtained values much higher than mine; his figures are shown in the second column of figures in Table IX. The reason for the difference between my/

my calculations and those of Clark is that the latter were calculated from the diameter of the aorta under no pressure. The figures obtained by the author are more probable in that they agree more nearly with those obtained by Volkmann and other observers who made direct measurements of the velocity of the blood flow in the carotid arteries. These results which are in the third column of figures in Table IX are quoted from Tigerstedt(26).

The blood velocities calculated from the measurement of the cross section of the aorta show that the aortic cross section varies in such a way that the velocity of the blood flow in the aorta is similar in animals of widely different sizes.

The Importance of Aortic Cross section

The usual figures given for aortic cross section are too small owing to the measurements being made at zero pressure, and this error is more marked in the case of the smaller animals.

The author's figures indicate that the aortic cross section of a man of 60 kilos is 6.1 sq.cm. whilst the usual figure given is 3.7 sq. cm.

The/

The work of the heart is divided into a kinetic and a static factor and can be estimated by the following formula given by Evans (27).

$$W = QR + \frac{MV^2}{2g} \quad \text{for each ventricle.}$$

- where Q = vol. of blood in c.c. expelled per sec.
 R = blood pressure in terms of cm. of blood.
 M = mass of blood ejected in grams per sec.
 V = velocity at which it is ejected in cm/sec.
 g = gravity constant (981 cm. per sec.²)

Then W = gram centimetres of work performed in unit time.

This shows that the work is divided into the static factor QR and the kinetic factor $\frac{MV^2}{2g}$

The kinetic factor is low during bodily rest but rises rapidly when the minute volume, and consequently the aortic velocity, is increased.

Clark (28) calculated from figures by Yandell Henderson that in an athlete these factors were as follows.

| Work per minute in gram centimetres. | | | |
|--------------------------------------|---------------|------------------|---------------|
| | Static factor | + kinetic factor | = Total work. |
| At Rest _____ | 1,520,000 | + 66,000 | = 1,586,000 |
| During exercise _____ | 4,700,000 | + 1,040,000 | = 5,740,000 |

These/

These figures were based on the assumption that the aortic cross section of an 84 kilo man was 5 sq.cm. If, however, the aortic cross section be taken as $5 \times \frac{6.1}{3.7} = 8.2$ sq.cm. then the velocity is considerably reduced and these figures become

| | Work per minute in Gm. centimetres | | |
|-----------------|------------------------------------|------------------|--------------|
| | Static factor | + Kinetic factor | = Total work |
| At rest | 1,520,000 | + 23,800 | = 1,543,000 |
| During exercise | 4,700,000 | + 385,000 | = 5,085,000 |

Thus in violent work the kinetic factor only rose to 8.2 per cent. of the static factor, instead of 22 per cent. which was the figure obtained when the calculation was based on the smaller value for the aortic cross section. This difference in the size of the aorta means a difference of roughly 11 per cent. in the work done by the heart during violent exertion.

The Relation of Coronary Cross section to Heart Weight

The relation between coronary cross section and heart weight is shown in Fig. 6. This graph gives the formula

$$\text{Coronary cross section in sq.cm.} = \left(\frac{\text{heart weight in gms.}}{1825} \right)^{0.73}$$

or/ better $236 \text{ CCS} = (H.W)^{0.715}$

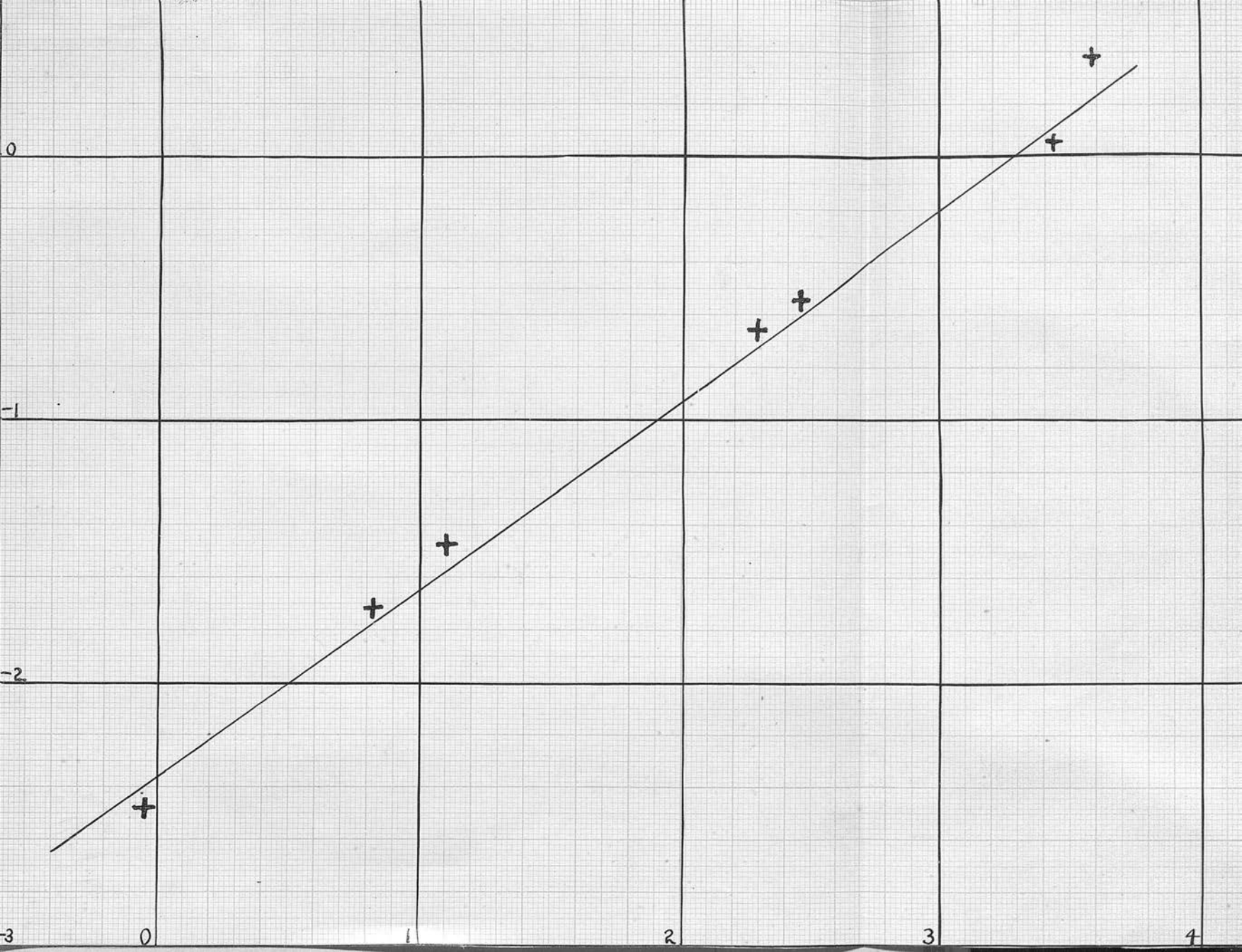
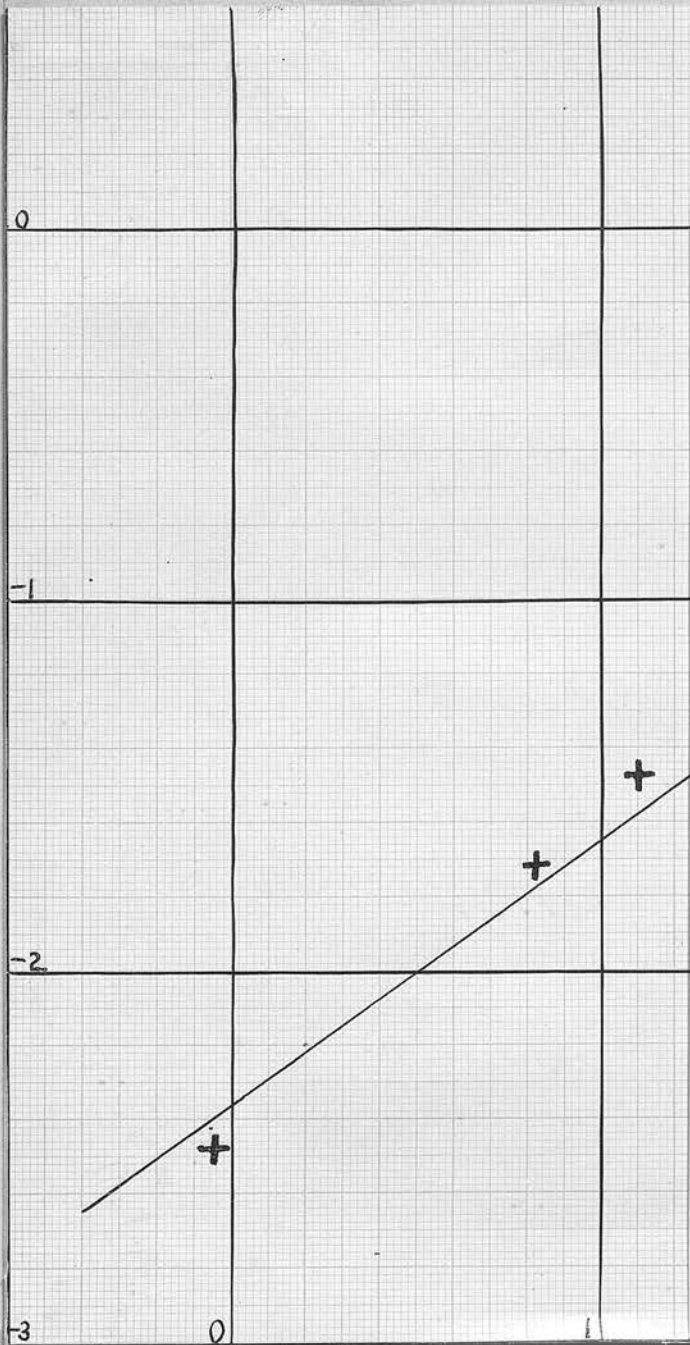


Fig. 6.



Abscissa - log heart weight in Gms.

Ordinate - log coronary cross section in sq.cm.

The curve follows the formula

$$\text{Coronary cross section in sq.cm.} = \left(\frac{\text{Heart weight in Gms.}}{1,825} \right)^{0.73}$$

$$CCS = \frac{(HW)^{0.725}}{230}$$

or $\log \text{ coronary cross section} = 0.73 \times (\log \text{ heart weight} - 3.26)$

This relation coronary cross section \propto (heart weight)^{0.73}

shows a definite divergence from the relation that was found between the aortic cross section and the body weight. The most obvious relation to investigate is that between the work done by the heart and the cross section of the coronary arteries. The frequency of the heart beat gives an indication of the work done by the heart. This relation between cardiac frequency and work is not exact because the larger animals have a higher blood pressure. (The blood pressure of the rat is about 100 mm. mercury, whereas the blood pressure of the horse is about 200 mm. mercury).

The blood supply per unit weight of heart should be indicated by $\frac{\text{coronary cross section}}{\text{heart weight}}$

and in Fig. 7 the cardiac frequency and coronary cross section per unit heart weight are plotted against the heart weight. These curves show the following relations.

Coronary cross section per gram heart weight = $\frac{0.0046}{(\text{heart wt.})^{0.16}}$

and cardiac frequency = $\frac{316}{(\text{heart wt.})^{0.27}}$

The/

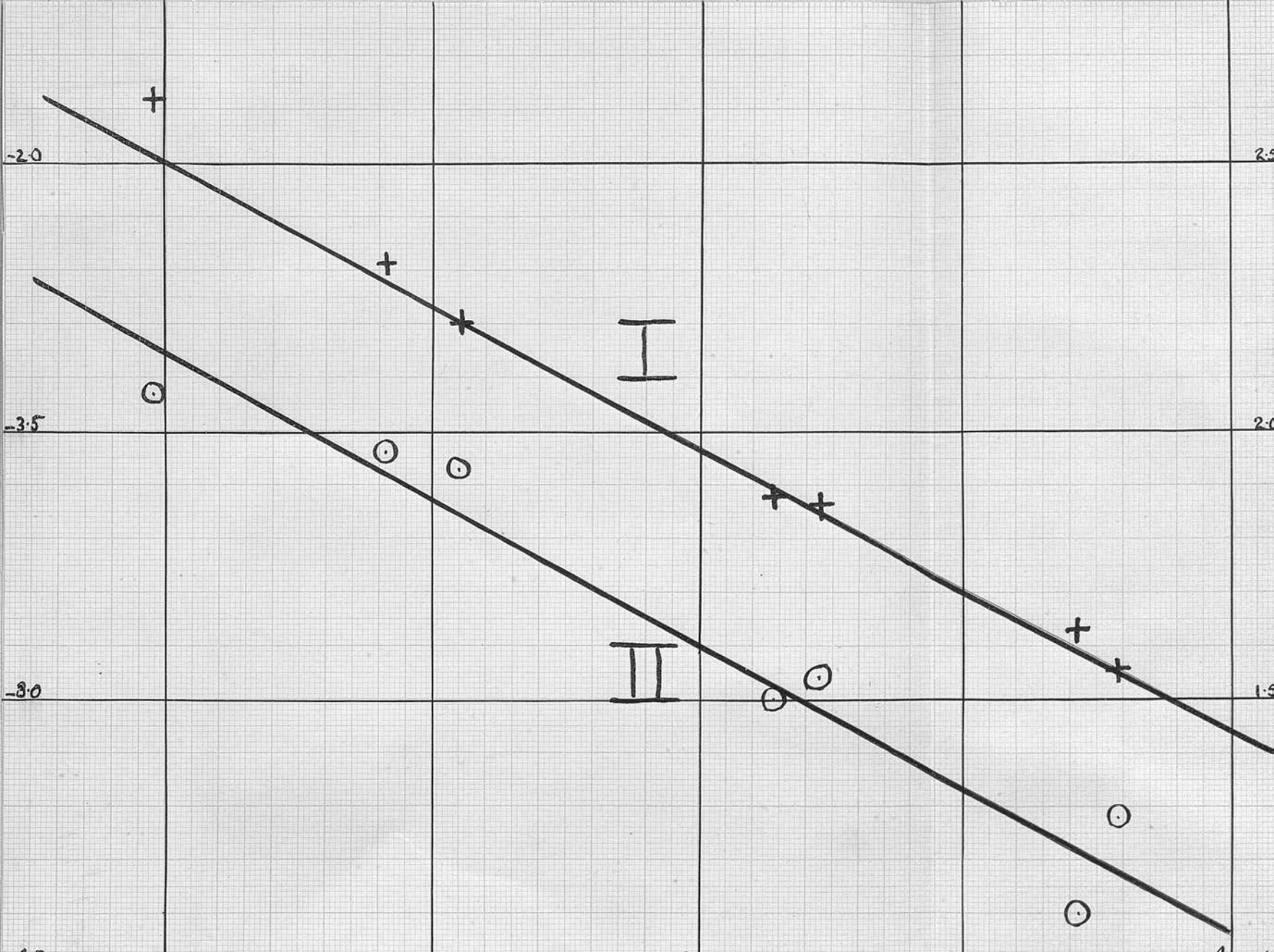
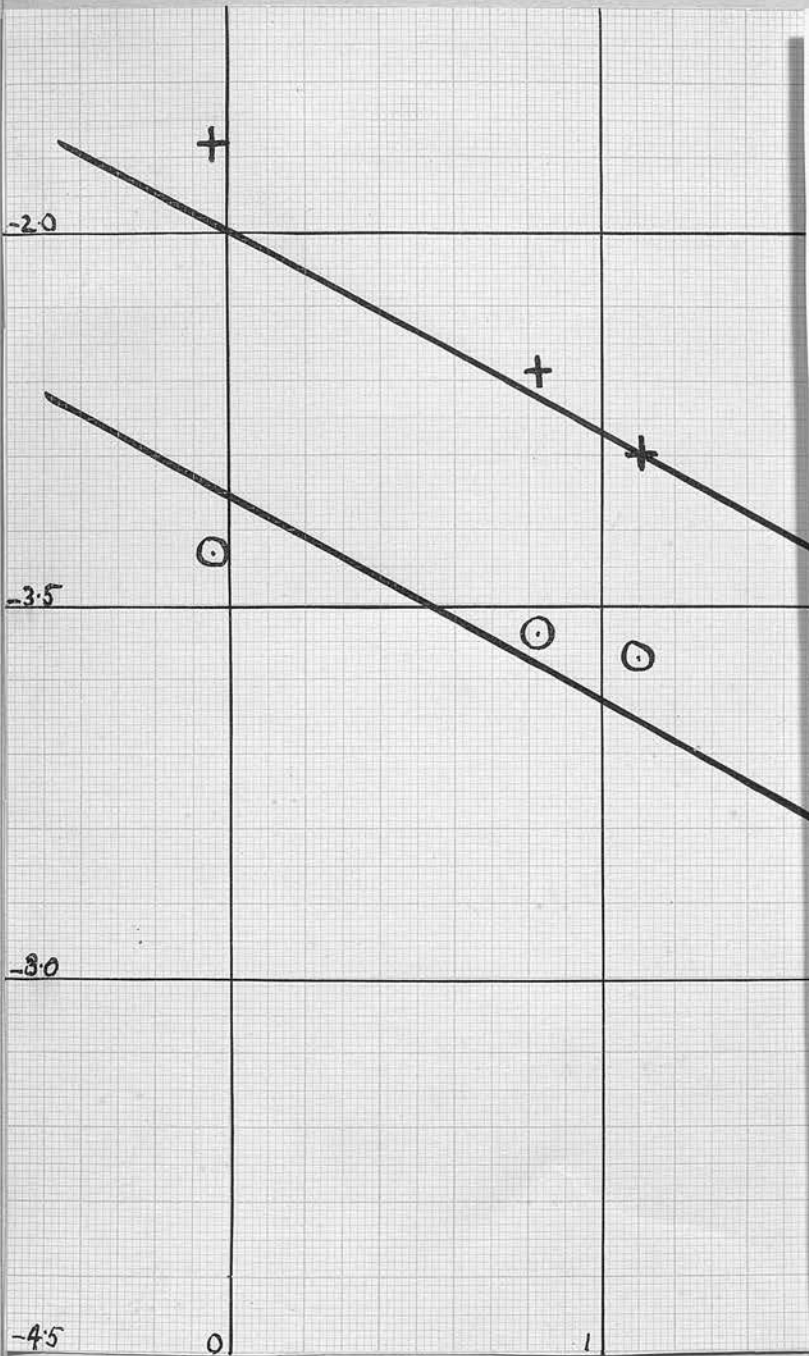


Fig. 7.



Abscissa - log Heart weight in Gms.

Ordinates- Left, log coronary cross section per Gm. heart weight.
in sq.cm.

Right, log cardiac frequency.

I = Coronary cross section per Gm. heart weight

$$= \frac{0.0046}{(\text{Heart weight in Gm.})^{0.26}}$$

II = Cardiac frequency =

$$\frac{3.6}{(\text{Heart weight in Gm.})^{0.27}}$$

The variation in the coronary cross section per unit of heart weight is therefore roughly parallel to the variation in the cardiac frequency. The variation in the cardiac frequency gives a rough measure of the variations in the work per unit weight of heart performed by the hearts of animals of different sizes, and the coronary cross section per unit of heart weight varies in the same manner as does the work performed.

This correlation is of interest since the respiratory exchange between the blood and the tissues occurs in the capillaries and the rate of blood flow is regulated by the contractile power of the smallest arterioles and the capillaries. There is therefore no obvious necessity for this variation in the cross section of the coronary arteries.

It has been shown in the case of the aortic cross section that the results suggest that the cross section of the aorta varies in such a way that the velocity of the blood flow in the aorta is similar in animals of widely different sizes. It would appear that the cross section of the coronary arteries varies so as to produce a similar constancy of velocity through the vessels.

Velocity of Coronary Flow.

Starling and Evans (29) found that the blood supply of the heart of a dog beating quietly in a heart-lung preparation was 60 c.c. per 100 grams per minute and that in asphyxia this might increase sixfold. The average weight of the cats used in these experiments was 2.7 kilos which is about one quarter the weight of a medium sized dog (12 kilos) and assuming that the heart's blood supply varies as (body weight)^{0.73}, then the blood supply of the cat's heart during bodily rest works out roughly at 87 c.c. per 100 grams per minute.

My average figures for the cat's heart are:

Weight 12.6 Gm. and coronary cross section 0.034 sq.cm.

That gives a rate of flow of

$$\frac{87 \times \frac{12.6}{100} \times \frac{1}{60}}{0.034} = 5.4 \text{ cm. per sec.}$$

Figures estimated by similar calculations for the other animals in the series are shown in Table X.

Table X./

Table X.

| Animal | Velocity of blood in coronary arteries in cm. per second. | |
|--------|--|----------------------|
| | (1) At rest | (2) Violent exercise |
| Rat | 7.0 | 42.0 |
| Rabbit | 5.4 | 32.4 |
| Cat | 5.4 | 32.4 |
| Sheep | 6.7 | 40.2 |
| Man | 5.9 | 35.4 |
| Horse | 5.6 | 33.6 |
| Ox | 8.2 | 49.2 |

From Table X it is seen that the velocity of the blood flow in the coronary arteries is fairly constant in this series of animals ranging in size from the rat to the horse.

Conclusions/

VI. CONCLUSIONS

- (1) Radiography of hearts into which lipiodol has been injected under a pressure equal to the normal systolic blood pressure of the animals, provides a method for measuring the diameter, and consequently the cross section of the aorta and coronary arteries.
- (2) The errors due to pressure, temperature and post mortem changes have been investigated and the necessary compensations have been estimated.
- (3) Measurements of the aortic and coronary cross sections have been made on the rat, rabbit, cat, sheep, man, horse and ox.
- (4) The relation between aortic cross section and body weight is similar to the relation between basal metabolism and body weight in this series of animals from rat to ox.
- (5) /

Conclusions contd.

(5) In this series of animals the aortic cross section appears to vary in such a way that the velocity of blood flow in the aorta is similar in all cases.

(6) In this series of animals the coronary cross section per unit of heart weight varies roughly in the same manner as the work performed per unit of heart weight.

(7) In this series of animals the coronary cross section appears to vary in such a way that the velocity of the blood flow through the coronaries is similar in all cases.

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