PRESSURE PULSES AND BLOOD PRESSURE VALUES IN UNANESTHETIZED DOGS

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At present two views are held concerning the relationship between left ventricular and aortic pressure curves as regards contour and ordinate value. The one, sponsored by Wiggers (5) on the basis of experiments on anesthetized dogs with open chests and subscribed to by many others, holds that the systolic portions of both curves are parallel and of approximately the same height, whereas the other, most recently sponsored by Hamilton and associates (2, 3, 4), maintains on theoretical grounds and experimental work on unanesthetized dogs that during systole the apical intraventricular pressure must and does exceed the aortic to insure that blood shall flow from the ventricle to the aorta. Failure to obtain curves showing such pressure differences (indicating low or zero velocity in the ventricular apex and high velocity in the aorta) is ascribed to various factors which tend to reduce the kinetic factor and hence minimize the excess ventricular pressure; such as reduction of cardiac output through anesthesia and surgical shock and connection of the intraventricular manometer to the upper portion of the ventricle, a region in which the blood has nearly attained the aortic velocity.

PROCEDURE. To obtain an answer to the question, attention was directed first of all toward devising ways and means of determining accurately the pressure pulses from the heart and arterial system of normal well-trained dogs, and secondly, toward making the circulatory system more accessible so that we could be sure of the exact location of our cannulae.

For this purpose the Wiggers universal manometer cannot be used because attachment to it of the necessary, long, small-bore cannula results in an inefficient instrument of low frequency. The small, hypodermic manometer of Hamilton (2) overcomes these difficulties and represents a distinct contribution to the tools available for investigating circulatory

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problems. In our work, the Hamilton type of manometer was used with various modifications as shown in figure 1. While the fundamental principle of the manometer (namely, a large effective mass combined with a very high volume-elasticity coefficient) has been retained, certain changes have been made which allow greater ease in mechanical manipulation and filling, greater sensitivity (larger curves) without sacrificing the manometer efficiency and which also give more uniform calibration curves.

The manometer proper consists of a thick walled brass cylinder 5 to 7 cm. long by 4 mm. internal diameter whose front end has been machined down so that after attachment of the membrane and mirror at B the manometer can be inserted into its carriage. A detachable lead tube, D, of varying length is attached to it by a threaded joint, E, and to the needle, S, by a tapered brass ring soldered to it so that it forms a sleeve joint with base, R, of the hypodermic needle. The making of the manometer in three sections has certain technical advantages. First, the manometer barrel can be easily filled by thrusting into it as far as its membrane, a brass tube or catheter, slightly smaller in diameter and connected to a sodium citrate bottle. The other portions of the manometer, after being jointed to the barrel, are then filled through stopcock A. Secondly, the sleeve connection at R allows removal and cleaning of an occluded needle without dismounting the manometer. Finally the manometer can be calibrated at various times during an experiment by shutting stopcock O, and opening stopcock A, which is connected to a sodium citrate bottle.

Although the telescope mounting of the manometer as used by Hamilton is satisfactory for some experiments, it lacks the flexibility and rapidity of adjustment that is so often required. Hence we have substituted the brass carriage shown in figure 1. The manometer, C, fits snugly into the solid brass block, F, and is held in place by set screws, G. This unit fits on its two lateral sides into a heavy brass casing, H, to which it is attached by a brass pin, P, thrust through the front end of F and H. This whole assembly is pulled snugly against I by means of the stout brass rod, L, (threaded at its lower end) and passing through brass block, K. Vertical
Fig. 2. Records of arterial and left ventricular pressures used for determining relative forms and pressure values under different dynamic conditions. A, typical calibration chart. B, frequency determination (135 per second). C and D, records taken before and after epinephrine injection in locally anesthetized dog. E, basal blood pressures from carotid loop and fixed ventricular apex. F, basal ventricular pressure in unoperated normal dog. In this and subsequent figures A.P. = aortic pressure; C.P. = carotid pressure; V.P. = left ventricular pressure; Time, 0.02 second.
movements of the manometer are obtained by adjusting screws, $M$, on the back portion of $H$. Lateral movements are obtained by two screws, $N$, attached to the non-movable section, $I$.

The aperture, $B$, upon which is placed the recording membrane utilizes the segment principle. For a membrane, shim brass and silver as advocated by Hamilton and associates and also heavy sheet rubber have been tried. However, the sensitivity with the metal membranes is so different at various pressure levels that they have been discarded and heavy rubber membranes tightly held in place by flexible wire have been substituted. With these membranes the calibration curves are more nearly uniform (fig. 2A) (except at quite low pressures where the sensitivity is somewhat greater) and remain unchanged for long periods of time. In addition sufficient sensitivity can be obtained at 5 meters’ projection (without sacrificing the efficiency of the system) to permit registration of fairly large curves capable of rapid scrutiny, whereas the curves obtained with the metal membranes generally require micro-calibration and analysis.

In using the membranes, we have occasionally observed the phenomenon of hysteresis, especially when the pressure is suddenly lowered in the manometer system. All experiments are checked for its presence and those in which the membrane does not follow rapid pressure changes are discarded.

At times the base line mirror (not shown in fig. 1) is mounted directly on an immovable point of the manometer carriage but we prefer placing it on a hinge attached in front to the carriage so that it can be rotated vertically or horizontally and independently of the recording mirror.

The lighting system and mirrors are essentially those described by Hamilton except that we have used a series of adjustable slits in front of a projection bulb, the filaments of which are in line with the manometers rather than a single vertical slit with the projection bulb filaments parallel to the manometers.

The manometers as used had frequencies ranging from 130 to 300 per second (fig. 2B), the actual frequency depending on the membrane and bore and length of the attached hypodermic needle.

These manometers were used on several types of dog preparations. In the first experimental series, the procedure of Hamilton was duplicated. In morphinized dogs, the left ventricle and proximal carotid artery were entered (after surgical exposure of the artery under procaine anesthesia) by hypodermic needles (18–20 and 20–24 gauge respectively) and connected to the manometer just described. In a second experimental series the arterial pressure was obtained from the aorta by means of a long trocar pushed down the carotid to the aortic valves and joined to the recording manometer. In addition in both series, the possible modifications induced by general anesthesia, epinephrine, and by opening the chest on the
relationship of the left ventricular and arterial pressure curves were studied. The subsequent opening of the chest in many of these experiments enabled us to determine the exact location of the needle in the ventricle and to evaluate the possibility of cardiac tamponade following ventricular puncture.

However both types of experiments have the drawback that the position of the intraventricular needle cannot be determined unless the animal is sacrificed. Hence a third series of animals was prepared. Quiet dogs were selected from stock and trained to lie untied for hours at a time on soft beds provided for them. They were then operated on under ether anesthesia as follows, to make the circulatory system more accessible for puncture. For recording intraventricular pressures, a portion of the rib over the apex of the heart was resected, the pericardium slit and then the apex of the left ventricle and its surrounding pericardium were sutured in circular fashion to the bordering intercostal muscles so that the apex was anchored just under the skin. Thus as soon as the intraventricular needle had penetrated the skin, it was in contact with the apex of the heart and we could be reasonably certain of the exact portion of the ventricle penetrated. To insure that the pressure in all regions of the ventricle was recorded, a long needle was inserted in a variety of ways; directly through the apex and for varying distances toward or to the base, and also laterally through the apex with the needle tip directed toward the base or apex of the heart.

To obtain pressure curves from the arterial system, a Van Leersun loop was made of the left carotid and approximately three weeks allowed for operative recovery. On the experimental day the proximal artery was entered by a short, straight needle without anesthesia or dissection. After withdrawal of the needle at the close of an experiment, the artery was gently compressed (2-3 min.) to avoid hemorrhage into the loop. These preparations, if not punctured too often, last a long time. Both arterial and ventricular punctures could be made repeatedly from day to day without any noticeable discomfort to the dog and without even a local anesthetic.

Results. In figure 2 C, D, are shown the changes that occur in the aortic and left ventricular pressure curves in a typical experiment in which the dog was maintained under different dynamic conditions. The dog, untrained and locally anesthetized, was from our second series in which the arterial pressure was taken from the aorta and the left ventricular pressure from the apical region by a hypodermic needle thrust through the lateral aspect of the ventricle. (The point at which the needle entered the

*We are greatly indebted to Doctors Beck and Mautz of the Department of Surgery for the cardiac operations and to Doctor Goldblatt of the Department of Pathology for preparation of the carotid loops.
ventricle was determined by sacrificing the animal at the end of the experiment.) The curves in figure 2 C were taken soon after the insertion of the hypodermic needle. The manometers differ slightly in sensitivity. The heart rate is 40 per minute although in most of the beats the rate was around 80, the variations being due to the normal sinus arrhythmia. During diastole the ventricular pressure is maintained at 15 mm. Hg and rises steeply during the ventricular isometric contraction period and then more gradually but still quite rapidly and smoothly throughout the duration of systole to reach a peak pressure of 164 mm. Hg. This is followed by a period of rapid pressure drop during the isometric relaxation period. The aortic curve parallels very closely that of the ventricle while the aortic valves are open with systolic and diastolic pressures of 168 and 108 mm. Hg. (The difference of 4 mm. Hg between the two systolic pressures is within the range of experimental error.)

If an excess of ventricular over aortic pressure is to be demonstrated, its presence should, in accordance with Hamilton’s reasoning, be magnified by the injection of a substance such as epinephrine which increases the velocity of the blood leaving the heart. Accordingly epinephrine was injected into a leg vein and the curves of D were taken. The systolic portions of the ventricular and aortic curves, although rising and falling more rapidly than in C, have essentially duplicate contours with an aortic pressure of 243/165 and a ventricular pressure of 237/22 mm. Hg. It is obvious that such curves showing agreement in contour and pressure values of their systolic portions differ from those reported by Hamilton. In order that the relative contours may be examined more in detail, the curves in figure 2 C, D, have been enlarged by projection and brought to identical scale in figure 3 A, B.

Such a relationship also holds regardless of the condition of the circulation. The curves in figure 3 C were taken later in the same experiment a few minutes after administration of sodium amytal anesthesia. The heart rate increases to 136 per minute, the aortic pressure drops to 126/89 mm. Hg and the ventricular to 121/14 mm. Hg. During systole the pressure curves agree in contour but both present a rounded contour with the point of maximum pressure in mid-systole. After giving epinephrine, the curves in D were recorded. The heart rate decreases to 92 per minute. The relative contours and pressure values of the curves agree with those in A and B. In E the chest has been opened and epinephrine injected. The systolic portions of the aortic and ventricular curves have similar rounded contours with the maximum pressure late in systole.

3 In all tracings shown in this paper epinephrine was given to accentuate any possible pressure difference between the left ventricle and aorta or carotid.

4 We are indebted to the Eli Lilly Co. for furnishing a generous supply of sodium amytal.
Fig. 3. Chart showing reconstructions from curves of figures 2, 4 (and also others) in which curves have been placed on same ordinate scale. Charts A, B = curves C, D of figure 2. Chart C = effect of general anesthesia. Charts D, E = effect of epinephrine after general anesthesia and opening chest respectively. Chart F = curve E of figure 4. Dotted line curve in A through E = aortic curve reconstructed to ventricular ordinate scale. Dotted curve in F = ventricular curve placed on aortic ordinate scale. Ordinates = millimeters of Hg.

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Such records definitely indicate that although the systolic and diastolic blood pressures and contours of the ventricular and aortic pressure curves are materially altered under different dynamic conditions, they always agree as to ordinate value and contour under any one condition.

To obviate the criticism that the ventricular needle (although in the lower third of the ventricular cavity) must be at the extreme apex to record the maximum ventricular pressure, curves were recorded from dogs of our third series in which the carotid pressure was taken from a Van Leersum loop with the needle opening directed toward the heart and ventricular pressure from the immobilized apex. The ventricular needle was inserted under the skin and while the apex was palpated, the needle was thrust into the apex and gradually withdrawn until sodium citrate under high pressure would scarcely flow through the needle. The needle was then advanced slightly further until the citrate level dropped rapidly. This was considered to be the apex of the heart.

As a preliminary step in most of these and subsequent experiments, blood pressure determinations were made under basal conditions. The dogs, carefully trained, were maintained under conditions such as obtain when a basal metabolic determination is made, that is, the animals were in a postabsorptive state and underwent a preliminary rest period of 15 to 30 minutes. Extraneous noises were excluded and finally no records were taken for some minutes after the insertion of needles or after a needle had been flushed with sodium citrate or heparinized Locke's solution. Rigid adherence to these conditions always results in blood pressures of the order of magnitude (or somewhat higher) of those shown in figure 2, E (124/85 mm. Hg) in which the carotid pressure was taken from a carotid loop and the left ventricular from the apex of the heart anchored to the chest wall. The ventricular curve in F approximates that in E and was taken from the lower portion of the left ventricular cavity of a well trained, basal dog under procaine anesthesia but in which the ventricle had not been sutured to the chest wall. This curve is added because it serves to emphasize that the operative procedures, which allowed us always to be sure of the exact location of the ventricular needle tip and which largely eliminated the possibility of puncturing a coronary vessel, did not embarrass the circulation or affect the pressure pulse.

Such pressures are considerably less than those reported by Goldblatt and co-workers (1) using the palpatory method on carotid loops and those of Hamilton (2) in supposedly basal dogs under morphine anesthesia. Our values are also much higher (168/108 mm. Hg) when obtained on morphine-ized dogs not well trained (fig. 2 C) or in which operative procedures are undertaken on the experimental day. Even with well trained dogs, systolic values of 140 to 170 mm. Hg are the rule unless the above precautionary measures are adopted.
After recording basal pressures the curves in figure 4 A, B, were taken with the above procedure before and after injection of epinephrine, the latter being given to magnify, if possible, any differences in aortic and ventricular pressures. As far as it is possible to judge of aortic pressure changes from curves recorded from the carotid, the contour and magnitude are essentially the same. That the apex and base of the heart also yield similar curves is evidenced in figure 4 C, D in which epinephrine had been given. In C the ventricular needle had been pushed through the apex so that its tip must have reached the base of the ventricular cavity. It was then withdrawn to the apex (as determined by the above test) and the curves of D recorded. When due allowance is made for the transmission time of the carotid pulse, the curves and relative pressures in figure 4 are similar to those of figures 2 and 3.

It is remotely conceivable that, since the needle opening was not directed toward the apex, the full magnitude of the end pressure in the ventricle might not have been recorded especially when the needle tip was at the apex. Therefore as supplementary tests on the same operated dogs, the ventricular needle was inserted laterally through the apex and with its opening directed toward the tip of the heart. Such curves, after the administration of epinephrine, are reproduced in figure 4 E. Since the sensitivities of the ventricular and carotid manometers are quite different in the curves of figure 4, representative curves (fig. 4 E) have been enlarged.

Fig. 4. Left ventricular and carotid pressure curves with the ventricular needle in various positions. A, ventricular needle at apex. B, ventricular needle at apex after epinephrine. C and D, ventricular cannulae at base and apex respectively after epinephrine. E, ventricular needle laterally through apex.
and placed on the same ordinate scale in figure 3 F to facilitate contour comparisons. The curves display no essential differences in relative forms and pressures from the others and need no further comment. The locus from which pressures are recorded and also the direction of the needle are immaterial in registering pressure pulses from the ventricle. We are therefore unable to repeat the results of Hamilton or to substantiate the dynamic theory of cardiac action evolved on its basis.

Discussion. Our records all indicate that there is no recordable region of the left ventricular chamber in which the systolic pressure is greater than any other. The question remains how curves such as those published by Hamilton and also by others were obtained. We attempted to duplicate such curves by inserting the ventricular needle so that sodium citrate under pressure ran into the manometer and through the needle very slowly or not at all. Such impedance suggests that the point did not lie free in the cavity and most probably was either in, or tightly pressed against the myocardium or papillary muscles. Under such conditions curves such as those of figure 5 were obtained from our third series of operated dogs. In A, the ventricular needle had been inserted through the apex and then withdrawn until citrate flowed through it with great difficulty. In B, it was inserted somewhat further until sodium citrate easily ran into the
ventricle. In the first curves the ventricular pressure rises to a maximum of 218 mm. Hg compared with 144 mm. Hg in the carotid, which indicates that there is a region of the heart (probably not in the ventricular cavity) from which ventricular pressures in excess of the carotid can be obtained. The registration of such curves is not restricted to the apex, for similar records showing excess ventricular pressures have also been obtained from the same type of preparation when the ventricle was similarly entered midway between apex and base and probably through the intraventricular septum.

Simultaneous ventricular pressure tracings differing in contour and magnitude can also be obtained in open chest experiments. At the time the curves of figure 5 C, D, were recorded, the heart was in poor condition. The upper curves were recorded by a manometer connected to a needle inserted into the upper portion of the left ventricular cavity and the lower curves by a needle used to explore different regions of the left ventricular chamber and wall. The curves in C were taken after the exploring needle had been inserted into the ventricle through the intraventricular septum about midway between base and apex and then partially withdrawn so that citrate under pressure scarcely flowed. The systolic pressure recorded in the lower curve is 130 mm. Hg as compared with 97 mm. Hg by the needle known to be in the ventricular cavity. Record D was taken as a control after the exploring needle had been reinserted into the ventricular cavity.

Such experimental results indicate a, that it is possible to obtain higher pressures from certain regions of the left ventricle than from the aorta, carotid or from other ventricular regions; b, that such higher pressures are not restricted to the apex but are obtainable from various portions of the ventricle; c, that such a pressure difference is not a function of the dynamic condition of the circulation for it can be found with high and low blood pressures, pulse pressures and stroke volumes, in normal and unanesthetized dogs with or without the heart exposed.

Since such pressure differences have never been recorded when the ventricular needle tip is free in the cavity but only occur when its opening is occluded to the extent that fluid flows with great difficulty through it, we have reached the conclusion that this higher pressure is not existent in the lumen of the ventricle.

SUMMARY

1. The relative contours and pressure values in the left ventricle and aorta or carotid artery of the dog have been studied by means of a modified Hamilton manometer. The manometers were connected to several types of dog preparations, (well trained basal dogs, normal dogs under local or general anesthesia, and also trained basal dogs in which the apex of the
heart had been previously sutured to the chest wall and an exteriorized loop of a carotid made), maintained under different circulatory conditions.

2. It has been found under a great variety of dynamic states of the circulation, and irrespective of the location of the cannula in the ventricular cavity, that the contour and pressure value of the systolic portion of the arterial curve reproduces accurately the ventricular pressure pulse.

3. Ventricular pressures considerably in excess of the aortic or carotid can indeed be obtained but only by placing the ventricular needle so that its opening is partially or wholly occluded during systole. Such curves are believed to represent technical artefacts and not the true pressure variations in the ventricle.

4. Basal arterial blood pressures from normal well trained dogs are not as high as generally supposed but give values approximating 124/85 mm. Hg.

REFERENCES