PHYSIOLOGICAL DILATATION OF THE HEART.

A STUDY IN CLINICAL PHYSIOLOGY.

BY

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IN *De Motu Cordis*, published in 1628, Harvey described the outstanding facts about the heart's action and the circulation of the blood. But it has remained to the twentieth century to probe into "the most essentially vital of the characteristics of the heart . . . its power of adaptation, of altering its activity—that is, the amount of work it performs at each beat, according to the requirements of the body."¹

This subject may, I believe, still be said to be in its infancy, but a good deal is known as to the nature of the response both to local and general requirements.

As to local needs, something is now known of the mechanism by which the circulation in whole areas is switched on and off by means of neuro-arterial control. We know, too, that the capillary system—which, if dilated all over the body at the same time, would accommodate the whole of the blood, so that in such circumstances the individual would rapidly "bleed to death into his capillaries"—is also possessed of a marvellous arrangement for the control of local areas, opening up those required and closing down the rest.

It is, however, with the total output of the heart, and especially with certain aspects of it, that the present communication deals. It would indeed be strange if the heart—"the Sovereign within, from which all power proceeds," as Harvey puts it—was unprovided with some arrangement for varying its activities. As a matter of fact it contains two such mechanisms, one for altering the pace at which it beats, and another for varying the output per beat; and to state that the activity of the heart is constantly varying within wide limits is merely to bring it into line with what is true of every organ in the body. While variations in frequency are obvious, and alterations of output are admitted, it appears that *physiological dilatation*, which seems to be a necessary corollary, is denied as a fact and even as a possibility by certain authorities. Consequently I came to review what I knew, or thought I knew, about this matter, with the result that my convictions are confirmed. Until starting on this investigation I had not realized that conceptions which I had held for years, and regarded as known truths, were based upon premisses concerning which but little is to be found in works upon the heart or in the ordinary textbooks on physiology. Personal experiences, conversations, and correspondence, confirming information to be found only in isolated monographs and scattered papers, were what I had to rely upon; and the bringing together in orderly sequence of the grounds on which these views depended has proved to be no very simple task.

Calculations, stated here in cubic centimetres and litres and elsewhere in ounces and pints, were involved; and the mere matter of weights and measures proved somewhat confusing, until it was realized that a simple unit, representing one of the elemental premisses, was available; for, as will be seen, the gallon may conveniently be taken as an average unit of the circulation, and variations between one and seven gallons are more easily visualized than are the relatives in litres (4.5 to 31). Consequently in what follows I have made use of British standard measures, inserting the corresponding metrical equivalents in brackets. Approximate figures are all that are aimed at or required; for, apart from the fact that the results of different workers using different methods are not in exact agreement, the individual differences in human beings, in bulk, weight, activity, and pulse rate, are sufficient to vitiate exact generalizations. Useful conclusions can, however, be stated simply, though doubtless open to criticism in detail, and making no appeal to those who do not accept the premisses—which I understand are taught by physiologists generally.

THE HEART'S RESPONSE TO EFFORT.

The Output of the Heart per Minute.

The amount of blood in the body of a healthy human being is kept constant by an elaborate physiological mechanism, and is about one-fourteenth of the body weight; so that in a man weighing 10 st. (63.5 kilos) the blood weighs about 10 lb., which means about 8 pints or 1 gallon (4.53 litres). By the "minute volume" is meant "the amount of blood circulating per minute"²; and in an individual in complete repose it is found that the whole of the blood circulates about once a minute, and consequently in a 10 st. man the minute volume is one gallon. This gallon of blood goes twice through the heart in the course of the minute, once through the right side and once through the left, so that the minimum total output of the heart in a minute is 2 gallons (9 litres), while the output of each ventricle corresponds with the "minute volume" and is 1 gallon.

In sedentary work the minute volume is doubled; in ordinary muscular work it rises to about 4 gallons (18 litres), while in the extremes of athletic effort, to quote A. V. Hill, "the total amount of blood in such a man's body . . . must circulate about seven times every minute."³ Consequently the normal "minute volume" may vary from 1 to 7 gallons (31 litres). This last figure corresponds exactly with E. H. Starling's estimate. Quoting Krogh's researches, based on quite different methods from those employed by A. V. Hill, Starling says⁴ of an athletic individual undertaking very hard work: "this means that the heart can pump the total blood contained in the body round the whole circulatory system six or seven times in the course of a minute." Douglas and Haldane,⁵ working on yet another system, got a higher minimum and a lower maximum, and found considerable dissimilarity between different individuals. Yet Haldane, when discussing the matter in 1923, and supplying me with figures which imply a minimum minute volume of $1\frac{1}{2}$ gallons, agreed to my statement that this minimum "is increased several-fold as muscular work is undertaken."⁵

Halliburton (1923)⁶ accepts Starling's figures, and says, "In fact, the heart may increase its normal output sevenfold." While gratefully accepting this additional authority, I submit that the sevenfold output, though due to "exceptional" is not dependent on "abnormal" conditions, and that the word "normal" in the above sentence should be replaced by "minimal." The normal output is liable to constant variation, and has wide limits.

Samson Wright⁷ accepts Hill's figures and appears to find confirmation from sources to which I have not had access. Personally I accept unreservedly A. V. Hill's statement⁸ that "there is no possible flaw in the argument or calculation, otherwise it would be difficult to believe the conclusion."

In this connexion it is interesting, as Hill suggests, to compare the output of the heart with that of a bathroom tap. Such a tap turned to a gentle stream (about a quarter on) will yield about a gallon (4.5 litres) a minute, the equivalent of the output of one ventricle in a resting subject. The same tap turned on full rush with good power behind it will yield 5 or 6 gallons (27 litres) in the same time. Both taps turned on full yield 11 to 12 gallons (54 litres) in the minute—less than the equivalent of the maximum output of the two ventricles working together. "It is extraordinary," says Hill,⁹ "that a pump weighing only about a pound" (when empty about 10 ounces) "can have such an enormous output."

To take a familiar contrast at the other end of the scale the maximum output of a Higginson syringe per minute is a pint and a half (840 c.cm.), or about one-fifth of the output of one ventricle in an individual at rest—that is, the minimum minute output of one ventricle. But, of course, the Higginson syringe is not supplied by an auricle.

The Frequency of the Heart Beat.

The normal frequency of the heart beat in healthy adults is stated by physiologists as between 70 and 80 per minute,¹⁰ and clinicians commonly place it at 72. Some healthy people have a pulse rate in the sixties, and a few in the nineties, or higher.

When we speak of "normal" in this relationship we refer to an individual at rest. The pulse often sinks lower during sleep; sedentary work will send it up into the eighties; while with muscular effort it commonly rises to over a hundred; and, apart from pathological conditions, emotion may quicken or slow down the pace. All these variations are within the true normal range, as is also the very rapid action induced by extreme athletic exercise, which A. V. Hill has recorded with a string galvanometer as high as 180 per minute.⁸ Consequently, for the purposes of this paper, the minute frequency of the heart beat may be regarded as ranging from 72 to 180, corresponding to a range of from 1 to 7 gallons in the minute volume of the blood in circulation. It is obvious that the extremes of frequency cannot alone account for the extremes of volume.

The Output of the Heart per Beat.

The output of the heart per beat, like the volume of the blood in circulation and the frequency of the heart beat, is constantly varying, the common limits being from about 5 to 10 fl. oz. (150 to 300 c.cm.), while in exceptional effort it may rise to 13 or 14 fl. oz. (420 c.cm.). The "minute volume" divided by the pulse rate will give the ventricular output per beat, and the total cardiac output is just double.

A few examples will suffice to illustrate the range of these variations. A subject at rest with a minute volume of 1 gallon (160 fl. oz.—4.5 litres) and a pulse rate of 72 will have a ventricular output of about 2½ fl. oz. (67 c.cm.) and a cardiac output of 4½ fl. oz. (135 c.cm.) per beat.

Sedentary work is said to double the minute volume (2 gallons or 320 fl. oz.—9 litres). The pulse commonly rises during such work, and my own at this moment is 86. Consequently my ventricular output should be 3.7 fl. oz. As, however, my weight is 11 st. and not 10 st., the calculation brings the ventricular figure to 4 fl. oz. and the cardiac to 8 fl. oz. (240 c.cm.) per beat.

In moderate muscular exercise the minute volume rises to 3 or 4 gallons (14 to 18 litres). The frequency of the pulse varies a good deal in different people, but a rise to 110 or more is common. If we take a 3½ gallon (16 litres) minute volume with a pulse rate of 110, we get a ventricular output of 5 fl. oz., and a cardiac output of 10 fl. oz. (300 c.cm.) per beat. Finally, with the extreme "minute volume" of 7 gallons, a pulse rate of 160 necessitates a ventricular output of 7 fl. oz., and a cardiac output of 14 fl. oz. Compare this with A. V. Hill's statement,¹⁰ about which he says "there is no possible flaw in the argument or calculation"; "this means that each side of the heart ejects some 200 c.cm. (close on 7 fl. oz.) per beat," at a pulse rate of 180.

Enough has been said to serve the purpose of this paper. But if the heart can vary its "minute output" by gallons, and its "stroke output" by half-pints, it doubtless has a fine adjustment by means of which its output can be varied by drachms, minims, and cubic centimetres. Indeed, when one realizes the constantly varying requirements of the human body—muscular, digestive, metabolic, excretory, mental, and emotional—one soon comes to look upon the heart as an organ of such perfect adaptability that no two consecutive beats are likely to have a precisely identical output.

The Varying Capacity of the Ventricle.

Though the auricles doubtless participate in the changes of volume which the heart undergoes, it is convenient to concentrate on the ventricles. In Starling's *Principles of Human Physiology*¹¹ the capacity of both ventricles is stated to be approximately equal, and to amount in man to about 140 c.cm. (nearly 4.7 fl. oz.) for each ventricle when "the heart is completely relaxed." The cavities of the auricles are stated to be somewhat smaller. Halliburton¹² says that "during life each ventricle is capable of containing about three fluid ounces of blood. The capacity of the auricles is rather less than that of the ventricles, the latter being partly filled with blood before the auricles contract."

From a general survey of the premisses already studied this estimate of the capacity of each ventricle would seem to conform with what must be very usual in the case of

an individual neither at complete rest nor at work, and I think we may take it as representing the condition of the normal heart as commonly seen on the screen or in a radiogram. The outline in the photograph is that of the peripheral pericardium, with the heart in full diastole. The smaller shadow of systole is lost in the larger one; and though, on the screen, one can observe the flicker of the systole, it does not last long enough for the eye to appreciate its extent before it is again overwhelmed by the diastolic picture. Moreover, the peripheral pericardium is non-contractile, and must to some extent obscure the movement. Neither a screen picture nor a radiogram of the heart has yet been obtained during active physical work; nor is it easy to examine the heart clinically under such circumstances. A. V. Hill has managed to get a string galvanometric record of the frequency of the heart beat in the case of an athlete at hard work. If it should ever prove possible to attach a small cinematograph apparatus to the chest of a man rowing in a boat race—or on some laboratory equivalent—a moving picture of the heart will be obtained, and the picture will be one of varying volume.

As we have seen in the previous section, the output of the heart per beat may vary from 4½ to nearly 14 fl. oz. (135 to 420 c.cm.), so that a capacity of 6 fl. oz. (180 c.cm.), to take Halliburton's figures, must be subject to some mechanism for reducing it by an ounce and a half (45 c.cm.), and for increasing it by 8 fl. oz. (240 c.cm.)—an increase which should about double the heart's size.

The diminished output need not detain us; the heart adapts its activities to a nicety to deal with a diminished income. It is with the capacity for *increasing* output that we are more particularly concerned. There is a difference of 3 fl. oz. (90 c.cm.) between Halliburton's "life capacity"—6 fl. oz. (180 c.cm.)—and the "complete relaxation" referred to by Starling—9 fl. oz. (270 c.cm.). Any increased capacity beyond this must be due to dilatation; but the process is probably all one. The dilatation, and subsequent contraction, are *vital* processes. "Each of the muscle fibres which make up the heart wall is lengthened," and with the lengthening the energy of contraction is increased.¹ "Within physiological limits the larger the volume of the heart the greater the energy of contraction."

There appears to be no valid reason why this vital lengthening should stop at the level of post-mortem "relaxation"; and, as I read it, this is Starling's view. "In these circumstances, therefore, the heart is dilated, . . ." and "it remains dilated over the whole period of increased work." "But in a healthy individual this condition is only temporary." "A contracted heart may be in a bad condition, and a dilated heart may be in a good condition."¹

Nor does Starling leave us in any doubt as to the mechanism by which the dilatation is brought about. Though other factors are at work, it is the increased venous inflow that starts the process. "If a man starts to run, his muscular movements pump more blood into the heart, so increasing the venous filling, while the central nervous system, by contracting the arteries of the abdomen, increases the peripheral resistance, raises the arterial pressure, and forces all the available blood through the active muscles. As a result the heart is overfilled during diastole, and is impeded from emptying itself in systole. . . . Its volume, both in systole and diastole, enlarges progressively, its muscle fibres lengthening and its energy of contraction increasing" until a balance is attained, and the ventricles have dilated to a capacity sufficient to equal the increase of the venous inflow.

For this process to be possible an adequate increase of coronary circulation is essential, and the point is strongly stressed in Starling's lecture. No less is it impressed on the mind of A. V. Hill. "During such activity," says Hill,⁹ "the heart is consuming as much oxygen as the whole of the body does when at rest." "Probably one of the factors which limit the capacity of the heart is the amount of blood which can circulate through the coronary system, and this may vary in different individuals."

Another factor is the physiological capacity for the lengthening of the individual fibres of which the wall of

the heart is composed. This, too, "may differ in different individuals," and it differs in the same individual at different ages.

PHYSIOLOGICAL DILATATION.

"The demonstration of the connexion between dilatation of the heart and energy of contraction does more than merely bring the behaviour of the organ into line with that of voluntary muscle. It enables us to form a picture of what is occurring in the heart in all the vicissitudes and changes in stress to which it is exposed in the course of a man's life."

Since, some ten years ago, I first read Starling's Linacre Lecture,¹ from which the above quotation is taken, the idea of physiological dilatation of the heart has formed a part of my general conception of its mode of action—the idea, to use familiar similes, that, superimposed on its Higginson-like contraction, it has a kind of concertina-like adaptability.* I have welcomed every circumstance, in my reading and experience, that has seemed to confirm this conception; and I have not doubted that clinically recognizable degrees must occur in individuals with youth, health, and a good coronary circulation. It would seem needless to stress what appears to me so obvious, were it not that there is little to be found about the matter in textbooks and treatises; and also that, as already stated, it is denied as a fact, and even as a possibility, by men of eminent scientific attainments.

It was only after these views had been impressed upon me that I came to realize the fact that the heart's action has never been observed while performing its most arduous tasks; and also that recognizable phases of dilatation are unlikely to occur except under very exceptional conditions of strictly limited duration. A man in the thirties and the forties may have more staying power than he had at twenty, but he can no longer "sprint," and it is during the short-lived efforts of extreme competitive athletics—limited by minutes even in the longest bouts, such as the Boat Race—that the maximum of the elastic stretching property, common to all youthful tissues, is likely to be elicited. Such extremes of effort are of necessity of short duration; all the fibres of the heart are at full stretch and the whole of them are in action at the same time. As soon as the sprint is over the heart seeks rest, and its action changes.

Among minor experiences which have seemed to illustrate this condition two stand out in prominent relief, and I conclude with a brief description of these, both of which I believe to be recognizable examples of physiological dilatation.

I was greatly impressed by one of the experiments exhibited in the Harvey film. As soon as the aorta is tied the volume of the heart commences to grow larger, and, with increased vigour of action, it appears to reach about twice its original bulk. Presently, the height of the struggle over, the beats become irregular and feeble, and, as the organ ceases to beat, it reverts to its original size. It would appear that nothing except an active and vital dilatation can account for an expansion which disappears so promptly.

Finally, though I have been told that there must be "some other explanation," I have never doubted that the following clinical experience of my own, which seems to be an isolated one, furnishes an example of the condition under discussion. I believe that similar experiences will occur to others; but it is only of late that I have realized how rare must be the opportunity for encountering this condition accidentally, and how difficult it may prove to observe it, even if arranged for.

A CASE.

The boy, aged 16, convalescent from influenza at school—where the doctor, having some doubts about his heart, had kept him fairly quiet till the holidays—was brought to me by his parents, then occupying a country house for a few months, at the beginning of the Easter vacation in 1923. He had been convalescent for a fortnight; he seemed perfectly well, and I could find no evidence of cardiac mischief or weakness. Consequently I advised that he should spend a week in getting fit, and then do what he liked.

About a month later the parents rang me up and asked if I could see him that afternoon to decide if he might join in the

school games and sports during the coming term. The family left the district a month or two later, and I have lost all trace of them; but I am sure I should have heard if anything untoward had occurred. I gave the opinion that he was all right, and might do anything and everything; but this decision was based upon the views I held about physiological dilatation of the heart.

The boy's appointment was for 3 o'clock, and, as he had not turned up at five minutes past, I looked down the road, and soon saw him pounding up the hill on a bicycle. He had cycled for about three miles when, passing a clock, he noticed that he was late. Consequently he sprinted the last mile, mostly uphill, jumped off his bicycle, and without pausing or speaking, burst into my room, stripped to the waist, and stood at attention still puffing. To my surprise I saw a very rapid, regular, and rather diffuse impulse, not obviously below the fifth interspace, but extending on a line with the nipple as far as the axilla. The pace was too rapid for easy counting, but before I had time to consider that phase, and had just noted the limit of palpable pulsation as "outside the anterior axillary line at the nipple level," the picture changed with dramatic suddenness. In a moment, "in the twinkling of an eye," the impulse disappeared from beneath my finger, the visible pulsation was gone, and a normal apex beat in the normal position was all that could be found. Concurrently, and instantaneously, the rate changed; the rapid action was gone, and was replaced by a regular normal action, with a frequency, I think, in the seventies, though here, again, I regret to say my scant notes do not state the pulse rate. I was profoundly interested and impressed, for I did not doubt, nor do I now, that I had seen the counterpart of the 7 gallon (31 litre) minute volume of the circulation, and the 14 ounce (420 c.cm.) output of the heart beat. All four chambers of the heart must have been dilated, and probably both ventricles were involved in the visible and palpable enlargement. The suddenness of the change, recalling the sudden ending of paroxysmal tachycardia, puzzled me; and yet, on reflection, it seemed but to add one more item of information as to the marvellous adaptability of the heart to all exigencies. "The muscular movements" which "pump more blood into the heart" came suddenly to an end, and the "minute volume" of the blood in circulation dropped from the 7 gallon to the 2 gallon equivalent. There was no excess of blood entering the auricles to fill the dilated ventricles, and there was no further occasion for rapid action. Consequently the "concertina" action ceased, leaving the "Higginson pump" working at a normal pace, to carry on the requirements of the diminished circulation. If I am wrong in these surmises, then "there must be some other explanation."

What I had seen, though it impressed me, did not much surprise me. Though the extent of the dilatation was greater than I should have expected, yet it seemed to fit in with what might have been reasonably anticipated, and I supposed that the condition was familiar to other observers. I did not then realize, as I do now, that my opportunity depended on a series of fortunate coincidences—a healthy youth, in good condition, observed at the immediate conclusion of a bout of severe effort. The circumstances could not have been more ideal if they had been planned. Had I not been waiting for him, had he not been late and conscious of it, or had he paused before (still at full strenuous effort) tearing off his garments, nothing unusual would have been observed.

If, in such a case, the pace slows down, as in the "run out" in a hundred yards race, the subsidence of the cardiac dilatation will be gradual, as noted in Starling's brochure. If, however, cessation of effort is abrupt, the change is instantaneous, as in the case described above. In either instance the heart regains its resting volume before, in ordinary circumstances, it can be examined; and the fact that the "shadows of hearts examined radiologically immediately after the race were not increased at all—in fact, they were smaller than on the following day"¹⁴—is only what would be expected. The whole system seeks rest at the earliest opportunity, and cardiac intake and output are both reduced to a minimum.

REFERENCES.

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* I am indebted to Dr. K. D. Wilkinson of Birmingham—an uncompromising opponent of the views here advocated—for this excellent musical metaphor.