Ventricular Pressure-Volume Relationships and Oxygen Consumption in Fibrillation and Arrest

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Pressure-volume relationships and myocardial oxygen consumption (VO₂) were obtained in an isolated heart during ventricular fibrillation, potassium-induced arrest, and isovolumetric contractions. The heart was found to be less distensible in fibrillation than in diastole or arrest. The VO₂ increased from 4.6 to 14.6 cc./100 Gm. LV/min. as the fibrillating ventricle was distended. During arrest the VO₂ remained constant despite ventricular distention. When the fibrillating ventricle was distended beyond a critical point coronary flow was compromised and the VO₂ decreased. Beyond and only beyond this point could the VO₂ be increased by the greater coronary flow induced by a higher perfusion pressure.

Introduction

With the advent of open-heart surgery there has been an increased interest in myocardial oxygen consumption during ventricular fibrillation.1-5 Recently in this laboratory a comparative study was made of myocardial oxygen consumption during normal work, arrest, and ventricular fibrillation in a series of cross-circulation experiments.6 It was noted at that time that in fibrillation there was considerable variation of the oxygen consumption per gram of heart from animal to animal. Furthermore, these results appeared to be at variance with the work of subsequent observers whose values for oxygen consumption during ventricular fibrillation were in general lower.1 It seemed possible that the oxygen consumption of the fibrillating ventricle might be affected by distention of the ventricular cavity. If one were to consider ventricular fibrillation as a state in which the myocardial fibers contract asynchronously at a rapid rate one might expect an increase in the tension of the fibrillating fibers to be accompanied by an increase in myocardial oxygen consumption—a relationship that has been demonstrated to apply to the ventricle-contracting in a normal sinus rhythm.7-8

Therefore investigation was made of the pressure-volume relationships and oxygen consumption of the isolated left ventricle under conditions of ventricular fibrillation, potassium arrest, and isovolumetric contractions.

Method

An isolated heart preparation was developed which is schematically shown in figure 1. Healthy mongrel dogs were anesthetized with chloralose (65 mg./Kg.) and urethane (650 mg./Kg.). Shortly after induction the animal was partially exsanguinated and the chest opened quickly. The aorta was clamped approximately 2 cm. above the aortic valve. Heart action was immediately stopped by 50 ml. of a 2.5 per cent solution of potassium citrate injected through a needle puncture into the aorta proximal to the clamp. The heart was then excised and placed in a cool saline solution which lowered its temperature to about 20 C. With as little delay as possible the isolated heart was prepared as follows:

A Lucite button was secured in the vicinity of the aortic cusps with a ligature passed under the left coronary artery. By this procedure the left ventricular cavity was completely isolated from the coronary circulation with the exception of thebesian flow which was small and measurable. The right coronary artery was ligated. The left atrium was trimmed off with the exception of a fringe remaining around the mitral ring. A Lucite cannula 2 cm. in diameter was fixed in the mitral ring by a ligature passed around this fringe. The bundle of His was ligated as were the inferior and superior venae cavae. A catheter (PE 190 to 285) was placed in the coronary sinus and led to the outside.
through the tip of the right auricular appendage. Cannulas were tied in the aorta and pulmonary arteries. The heart was then ready for perfusion, the above preparation requiring an average of 45 min.

Healthy donor dogs served as a source of oxygenated blood. They likewise were anesthetized with chloralose and urethane after having been premedicated with 30 mg. of morphine sulfate. Following induction the donor dogs were tracheotomized. Pulmonary ventilation was maintained with a Starling pump. The femoral artery and vein were cannulated on one side for connection with the perfused heart.

As can be seen from figure 1, blood was pumped from the donor dog to a reservoir of adjustable height from which the oxygenated blood passed through a filter and a Shipley-Wilson rotameter and entered the coronary circulation of the isolated heart through the cannula in the aorta. The pulmonary cannula of the isolated heart was attached to the inflow of a pump which maintained a negative pressure of about —10 mm. Hg. Two tygon drainage tubes, 5 to 7 cm. in length, were placed in the right ventricle and led out through the pulmonary artery. These facilitated the return of blood from the coronary sinus and served to avoid distention of the right ventricle. The venous blood was returned to the donor through a second reservoir and filter.

One orifice of the mitral cannula was connected to a pressure transducer* through non-distensible tubing. The other orifice was connected to a syringe, with which the ventricular volume could be varied at will, while the developed pressures could be recorded. Pressure-volume points were obtained by thoroughly evacuating the ventricular cavity with a syringe, injecting a known volume of saline, and allowing 2 min. for equilibration prior to blood sampling. Volumes were rechecked following the sampling. The procedure was repeated in order of increasing volumes. Thebesian flow from the coronary vessels into the ventricular cavity was found to be in the vicinity of 1 to 2 ml./min. when the ventricular cavity was at atmospheric pressure. This source of error in the determination of ventricular volumes had to be considered at low levels of intraventricular pressure. As the intraventricular pressure was increased there was an accompanying reduction in Thebesian flow causing a negligible error at the higher ventricular pressures.

Small leads were attached to the epicardium for the purpose of stimulation of contraction and recording of the electrocardiogram. The stimulating current was provided by an electronic stimulator.* Ventricular fibrillation was induced by an electric shock of 60 cycles A.C. Higher currents of 60 cycles A.C. served to defibrillate.

Metabolic studies during potassium-induced arrest were obtained after rapid injection of 10 to 20 ml. of 5 per cent potassium citrate into the coronary circulation followed by a constant infusion of 0.3 ml./min. of the same solution. Samples of coronary sinus blood and aortic inflow were obtained through a catheter. These were analyzed for oxygen content by the method of Van Slyke and Neill. Myocardial oxygen consumption was calculated as the product of coronary flow and coronary arteriovenous oxygen difference. At the end of each experiment the left ventricle was weighed in order to determine myocardial oxygen consumption per 100 Gm. of left ventricle. Throughout the experiment the temperature of the heart was maintained at 38 to 39 C. by a constant temperature bath which also served to warm coils through which the perfusing blood was conducted.

**Results**

Ventricular Fibrillation

Pressure-volume curves during ventricular fibrillation were obtained in 13 experiments. The upper panel of figure 2 shows a typical pressure-volume curve of the fibrillating ventricle as represented by the solid line. The dashed line represents the diastolic pressure-
volume curve of the same heart not fibrillating but contracting isovolumetrically. In both diastole and ventricular fibrillation there was an increase in pressure as the ventricle was distended. At any given pressure the intraventricular volume was smaller in ventricular fibrillation than it was in diastole.

The second panel in figure 2 represents coronary flow. Initially the coronary flow in ventricular fibrillation increased concurrently with the increase in intraventricular pressure. When the intraventricular pressure was raised, on the average, to above 60 mm. Hg, the coronary flow started to decline.

The lowest panel in figure 2 represents the oxygen consumption of the fibrillating ventricle. In all experiments an increase in oxygen consumption accompanied an increase in the intraventricular volume and pressure. In 13 experiments the average oxygen consumption of the fibrillating ventricle rose from 4.6 cc./100 Gm. LV/min. at 0 intraventricular pressure to 14.6 at 60 mm. Hg intraventricular pressure. When the intraventricular pressure reached 60 mm. Hg and the coronary flow started to decline there was a concomitant decrease in the myocardial oxygen consumption.

In 4 experiments the coronary perfusion pressure was increased from 85 to 115 mm. Hg at various ventricular volumes. Figure 3 illustrates one of these experiments. At the smaller intraventricular volume, an increase in the coronary perfusion pressure from 85 to 115 mm. Hg (as indicated by the X's in fig. 3) was accompanied by a small increase

Circulation Research, Volume VIII, January 1960
in coronary flow, a reduction in coronary arteriovenous difference, and no significant change in oxygen consumption or intraventricular pressure, when compared with a comparable point on the PV curve obtained with a perfusion pressure of 85 (solid line). At larger intraventricular volumes, however, an increase in the coronary perfusion pressure resulted in a large increase in coronary flow, little change in the coronary arteriovenous difference, an increase in the oxygen consumption and an increase in the intraventricular pressure. The dotted line in figure 3 represents a diastolic pressure-volume curve obtained when the heart was contracting isovolumetrically.

**Potassium Arrest**
In 9 experiments pressure-volume curves were obtained during potassium arrest. These did not vary significantly from the pressure-volume curves obtained during diastole when the heart was contracting isovolumetrically. The large black dots in figure 4 represent points obtained in one experiment during potassium arrest. In all 9 experiments an increase in volume during potassium arrest was accompanied by an increase in intraventricular pressure, a decrease in coronary flow, and an increase in arteriovenous difference. In 8 of these experiments distention of the ventricle caused no significant change in the myocardial oxygen consumption, in contrast to the changes seen during ventricular fibrillation (solid line). The average oxygen consumption for the arrested ventricle was 1.5 cc./100 Gm. LV/min.

**Epinephrine During Potassium Arrest and Ventricular Fibrillation**
At any given volume during ventricular fibrillation single injections of epinephrine invariably were accompanied by an increase in both intraventricular pressure and coronary flow. In one experiment in which oxygen consumptions were obtained, an intracoronary infusion of epinephrine of 10 µg./min. into a fibrillating ventricle held at a constant volume was accompanied by a two-fold increase in both the intraventricular pressure and the oxygen consumption. During potassium arrest single injections of epinephrine were accompanied by no change in intraventricular pressure. The introduction of epinephrine during potassium arrest produced spontaneous ventricular beats and made comparable metabolic studies impossible.

**Oxygen Consumption and Tension During Ventricular Fibrillation**
At any volume the algebraic difference between the diastolic pressure and the pressure obtained during ventricular fibrillation can be considered to be the pressure developed by
the fibrillating ventricle. By the LaPlace principle, the tension per centimeter of ventricular diameter, assuming a spherical shape, is a function of the pressure and the cube root of the volume. Figure 5 is a plot of oxygen consumption versus developed tension in 4 experiments. In the lower right hand corner those points marked by the arrows are those in which the coronary flow was greatly reduced by a high intraventricular pressure. The point marked X was obtained after the perfusion pressure was increased.

Discussion

The myocardium during ventricular fibrillation is less compliant than in the diastolic period of normal contractions. It is, as a whole, in a complex state of sustained contraction. Consequently, the fibrillating ventricle in a sense "develops" a sustained pressure upon any imposed volume by an amount measured from the pressure during diastole or potassium arrest at the same volume. The myocardial oxygen consumption during fibrillation is proportional to the developed pressure and tension. This is consistent with the concept that myocardial oxygen consumption is related to tension. It is equally consistent with the concept that myocardial oxygen consumption is a function of diastolic fiber length regardless of the character and amount of external work evolved. In any case it is clear that the oxygen uptake of the fibrillating ventricle may vary widely, depending on its contained pressure even though it is doing no external work.

The increase in coronary flow that accompanies the increase in myocardial oxygen consumption is evidence that the isolated heart is capable of active vasodilation in the face of higher metabolic demands. As the ventricle is distended during potassium arrest coronary flow decreases. Conversely, as the ventricle is distended during ventricular fibrillation coro-
nary flow initially increases. This increase in coronary flow occurs at a constant perfusion pressure, which, by itself, might be expected to decrease coronary flow as it does in a heart stopped in potassium arrest (fig. 4). In addition, the administration of epinephrine to a fibrillating ventricle held at constant volume was invariably accompanied by a rise in both intraventricular pressure and coronary flow.

When the fibrillating ventricle is distended by pressures of 60 mm. Hg or more, a reduction in coronary flow is accompanied by a fall in myocardial oxygen consumption and intraventricular pressure. This suggests that flow has become inadequate to allow a sufficient diffusion gradient of one or more metabolic substances.

Our values for oxygen consumption during ventricular fibrillation agree with those of others if we assume that in the quoted studies there was no distending pressure within the ventricles. In addition our present data may help to explain the somewhat high values obtained in a previous study in this laboratory when the hearts could have been distended by retrograde flow in a cross-circulation preparation.

In potassium arrest there was no significant alteration of myocardial oxygen consumption when the heart was distended. In view of this and the fact that the pressure-volume curve during arrest coincided with the pressure-volume curve during diastole, either there is no diastolic "tonus" or else potassium does not alter it, and the oxygen cost of maintaining it is not detectable by this method.

Our average value for myocardial oxygen consumption during potassium arrest agrees with the findings in a previous study where the implications were discussed.

Summary

A preparation is presented in which it is possible to obtain isovolumetric pressure-volume relationships and oxygen consumption in an excised heart. For any given volume a higher pressure was developed by the fibrillating ventricle as compared with the ventricle in diastole or arrest. In all experiments there was an increase in oxygen consumption of the fibrillating ventricle as the intraventricular pressure and volume were increased. This increase in oxygen consumption was related to the tension developed in the fibrillating ventricular wall. There was no significant change in the oxygen consumption of the arrested ventricle as the intraventricular pressure and volume were increased. In all cases where the pressure and volume inside the fibrillating ventricle were increased beyond a critical point the coronary flow and oxygen consumption decreased with any further increase in intraventricular pressure. Beyond and only beyond this point did an increase in the perfusion pressure result in an increase in oxygen consumption and intraventricular pressure.

Acknowledgments

The authors wish to express their appreciation for the technical assistance of Louis Freni, Philip Waithe, Eleanor Root, and David Pollard.

Summario in Interlingua

Es describite un preparato in que il es possibile determinar relationes isovolumetric de tension a volume e valores de consumption de oxygeno per le corde exeitite. Pro omne volume particular, un plus alte tension esscva disveloppate per le ventriculo fibrillante quo per le ventriculo in diastole o arresto. In omne le experimentos il habeva un augmento del consumption de oxygeno del parte del ventriculo fibrillante quando le tension e le volume intraventricular esseva augmentate. Iste augmento del consumption de oxygeno esscva relacionate al tension disve-loppate in le pariete del ventriculo fibrillante. Esscva notate nullo significative alteration del consumption de oxygeno in le ventriculo arrestate quando le tension e le volume intraventricular esseva augmentate. In omne le cases in que le tension e le volume intr le ventriculo fibrillante esseva augmentate in ultra de un punto critic, le fluxo coronari e le consumption de oxygeno diminuieva si tosto que le tension intraventricular esseva augmentate additionemente. In ultra de iste punto critic, e solmente in ultra de illo, un augmento del tension de perfusion resultava in un augmento del consumption de oxygeno e del tension intraventricular.

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Circ Res. 1960;8:260-266
doi: 10.1161/01.RES.8.1.260

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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