The development of catheterization and indicator dilution techniques has made it possible to measure the volume of circulating blood within many organs in the intact animal. Hirche and Lochner 12 injected measured amounts of dye into the coronary arteries of dogs and recorded the subsequent time course of dye concentration in blood from the coronary sinus. From this single curve both coronary blood flow and mean coronary circulation time were obtained, and the corresponding volume of circulating coronary blood was calculated. In the present studies circulating coronary blood volume (CCBV) was measured in dogs by a somewhat different approach, using independent isotope and dye injection methods to measure the rate of coronary blood flow and the coronary circulation time.

Methods

Eleven dogs weighing 13.1 to 23.4 kg were anesthetized with 26 mg pentobarbital per kg body weight and given 50 mg heparin intravenously. Catheters were passed into the pulmonary artery, right atrium, and the root of the aorta. A catheter, with two parallel lumina terminating in separate distal openings, was placed in the coronary sinus to permit withdrawal of blood continuously for determination of isotope content, and intermittently for recording of dye curves. The distal opening in the catheter used for continuous withdrawal was 4 cm beyond the proximal opening. The latter was placed as near the mouth of the coronary sinus as possible for optimal measurement of the mean coronary circulation time. This placement was made with the air of preliminary injections of dye into the right atrium, followed by recording of dye curves to rule out aspiration of right atrial blood by the coronary sinus catheter. The locations of all catheters were verified at autopsy.

Mean femoral arterial pressure, mean right atrial pressure, and heart rate were recorded frequently before and during a 10-minute period of study. The results in two dogs were discarded because a steady hemodynamic state was not maintained.

Determination of coronary blood flow

Rb 86 in 10 ml 0.15 M NaCl was injected intravenously at a continuously decreasing rate to maintain a stable concentration in arterial blood. 3 Blood was aspirated simultaneously at a constant rate of 0.49 ml/min from the femoral artery and from the distal orifice of the coronary sinus catheter. After 10 minutes, the heart was excised and the superficial fat removed by dissection. The remainder was weighed, digested in HNO3, and the Rb 86 content determined by scintillation counting. Mean myocardial blood flow was calculated by the Fick procedure from the total amount of Rb 86 taken up by the heart during the infusion period and the mean difference between isotope concentrations in arterial and venous blood.

Determination of mean coronary circulation time

During the period of Rb 86 infusion a series of dye dilution curves was recorded from the coronary sinus and aortic root using Waters X-300 densitometers of demonstrated linearity. For each measurement, 2.5 mg indocyanine dye (Cardio-Green) in 1 ml water was injected into the pulmonary artery over a period of less than 0.1 second. Blood was withdrawn from the aorta and coronary sinus at a rate of 18.4 ml/min through catheters which were of the same length and internal diameter. At least three sets of dye curves were recorded in each dog during or within 15 seconds prior to the study period. The dye concentration curves were read at 0.1-second intervals from a six inch oscillographic record, and the semilogarithmic downslopes were extrapolated to 1% of the peak value. The mean circulation time for each curve was calculated 4 and the differences of these times accepted as the mean coronary circulation time. In no dog did the separate values of mean
coronary circulation time differ by more than 9% from their mean.

Results

The mean circulating coronary blood volume (CCBV) in nine dogs was 14.2 ± 2.2 ml (sd)/100 g lean myocardium. The average of the mean coronary circulation times was 9.2 ± 2.4 seconds, and coronary blood flow averaged 97.3 ± 22.4 ml/100 g/min. Representative dye curves from one study are illustrated in figure 1.

CCBV did not show a wide range of values, the coefficient of variation being but 15.8%. CCBV was not correlated significantly with the rate of coronary blood flow or the mean coronary circulation time. However, the rate of coronary blood flow and the mean coronary circulation time were inversely related, as expected (fig. 2). CCBV was related inversely to the heart rate, which ranged from 126 to 212/min (fig. 3A). No significant correlation (P > 0.1) was found between femoral arterial blood pressure or right atrial pressure and CCBV. The range of variation was small, arterial pressure being 108 ± 11 mm Hg and atrial pressure + 21 ± 17 mm saline. Therefore the results do not provide evidence against a possible relationship of these factors under a wider range of conditions. Heart rate and mean coronary circulation time were related, but heart rate and coronary blood flow were not (fig. 3B and C).

Use of the shortest coronary circulation time as an index of coronary blood flow has been suggested.5, 6 The shortest coronary circulation time in the present series of dogs was estimated from the time lag between the first recording of dye in the aortic root and coronary sinus curves. It averaged 4.0 ± 0.8 seconds. Its relation to mean coronary circulation time and to coronary blood flow is shown in figure 4.

Discussion

Early studies of coronary blood volume were done using the isolated heart.7-10 In the
most recent of these, Salisbury et al. measured changes in the coronary blood volume by observing fluctuations in the weight of the isolated, perfused, artificially paced heart. They found a linear relationship between coronary blood volume and coronary flow in fresh preparations, a nearly linear relationship between coronary blood volume and coronary arterial pressure from 30 to 125 mm Hg, and an inverse relationship between coronary blood volume and heart rate with a regular rhythm. The last association was confirmed in the present studies. No relationship of CCBV to coronary flow or to arterial blood pressure was observed in the range of variation present in these animals.

In the studies of Hirche and Lochner, dye was injected into either main branch of the left coronary artery, and time-concentration curves were registered from a catheter situated in the coronary sinus. Both coronary blood flow and mean circulation time were determined from analysis of the same dye curves. To approximate the actual rate of coronary blood flow it was assumed that the dye was thoroughly mixed in the blood within the coronary sinus and two manipulations of the data were performed. First, 10% was subtracted from the measured flow under the assumption that approximately 10% of the dye injected into a main branch of the left coronary artery does not reach the coronary sinus. Second, their findings indicated that 1.5% of the coronary sinus outflow was contributed by the right coronary artery; accordingly another 1.5% was subtracted from the measured flow. They found a mean value for the CCBV of 12.4 ± 1.0 ml/100 g myocardium, a mean coronary circulation time of 8.7 seconds, and a mean coronary blood...
flow of 87.3 ± 7.1 ml/min/100 g. No correlations of their results with other hemodynamic observations were reported.

The studies of Hirche and Lochner assume that blood flow throughout the heart is identical with flow in the left ventricle. Our determination of coronary blood flow assumes that the mean arteriovenous difference in Rb86 concentration is the same across all parts of the myocardium. Both methods assume that all transcoronary circuits have the same mean circulation time. While these assumptions limit the accuracy of these determinations of CCBV, the results are believed to be close approximations to the true values. The inverse relationship of heart rate and CCBV may be explained by the mechanical effect of systole on the myocardial vessels. Variations of heart rate produce changes in the relative duration of systole and diastole, and in the absolute diastolic filling time available to the vessels within the myocardium. The presence of tachycardia associated with anesthesia in the present studies suggests that CCBV may be even larger at normal heart rates. The regression equation for the data in figure 3A indicates an expected CCBV of 20.6 ml/100 g at a heart rate of 100/min.

In these studies the shortest coronary circulation time was a poor index of the rate of coronary blood flow (fig. 4B). The mean coronary circulation time would have been a more nearly reliable guide (fig. 2). The large size of the CCBV, and its relation to heart rate, are important factors in evaluating techniques designed for estimation of coronary blood flow in man by precordial monitoring of the circulation of a bolus of radioactive blood.11-13

Summary

The circulating coronary blood volume was calculated in dogs from independent determinations of the rate of coronary blood flow and the mean circulation time from the root of the aorta to the mouth of the coronary sinus. The average value was 14.2 ± 2.2 ml/100 g lean myocardium. Coronary blood volume was inversely related to the heart rate, which ranged from 126 to 212 beats/min, but was not correlated with other hemodynamic variables within the relatively narrow range of values present.

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Circulating Coronary Blood Volume
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