Evaluation of Venous Bypass Grafts from Aorta to Coronary Artery by Inert Gas Desaturation and Direct Flowmeter Techniques

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Abstract Blood flow through aorta-to-coronary artery bypass grafts has been measured selectively in 16 patients at or within 6 wk after operation. Inert gas desaturation curves were obtained from coronary venous blood samples after a 7–15 min infusion of dissolved H_2 directly into the graft. Samples were analyzed chromatographically and curves resolved to 1–3% of initial H_2 concentrations. Average flow per unit volume (F/V) was 67 ±21 (SD) ml/min per 100 g. Semilogarithmic plots showed F/V to be distributed heterogeneously in every case. In nine studies at operation, H_2 measurements of average F/V were combined with electromagnetic measurements of total flow to estimate revascularized tissue mass. Electromagnetic flows ranged from 25 to 170 ml/min and averaged 69 ml/min. Tissue mass ranged from 46 to 155 g and averaged 88 g. We conclude that bypass grafts provide nutritive flow to significant amounts of myocardium at and shortly after operation. However, nutritive flow is not distributed evenly throughout the revascularized segment. The majority of the segment has a F/V within the accepted range of normal but there remain areas in which F/V is reduced significantly. The combination of inert gas and electromagnetic techniques allows a revascularized area to be characterized in terms of total flow, F/V, and tissue mass.

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INTRODUCTION

Although the large majority of aorta-to-coronary artery bypass grafts remain arteriographically patent in the first 1–2 yr after operation (1), relatively little information has been available about the amount of blood flow supplied by the grafts. Existing measurements have usually been obtained with an electromagnetic flowmeter at the time of operation and have necessarily been confined to estimates of total graft flow in milliliters per minute. The present investigation utilized inert gas techniques to add information concerning flow per unit volume (F/V)[1] of revascularized tissue, the uniformity of flow within the revascularized segment, and the absolute mass of the segment. Studies were performed at the time of operation and during the first 2–6 wk after operation, and included methodological precautions necessary to include areas of reduced flow when perfusion is distributed in a heterogeneous fashion (2–4). The findings indicate that arteriographically patent grafts provide nutritive flow to appreciable amounts of myo-

[1] *Abbreviation used in this paper:* F/V, flow per unit volume.

cardium but that flow is not distributed evenly within the revascularized segment. The majority of the segment has a F/V within the accepted range of normal but there remain areas in which F/V is reduced significantly. The combination of inert gas and electromagnetic techniques at the time of surgery allows a revascularized segment to be characterized in terms of total flow, F/V, and absolute tissue mass.

METHODS

A total of 21 studies have been performed in 16 patients (10 at the time of operation and 11 in the early postoperative period). Ages ranged from 37 to 62 and averaged 51 yr, and all patients were male. Although the majority of patients had two or three grafts performed, inert gas studies were usually confined to a single graft. Decisions to offer bypass surgery were based on the presence of angina pectoris which had not responded satisfactorily to conventional medical therapy and which was associated with $>75\%$ narrowing of a major coronary artery and an arteriographically demonstrated vessel >2 mm in diameter beyond the obstructive lesion. Arteriographic studies included both 35-mm cinearteriograms obtained with an overframed 6 inch image intensifier and high resolution 35×35-cm films exposed sequentially in a rapid changer.[2] Operative studies were performed after hemodynamics had stabilized following cessation of cardiopulmonary bypass. Postoperative studies were carried out during routine follow-up cardiac catheterization 2–6 wk after operation.[3] Premedication in the postoperative studies included 0.025–0.050 g promethazine, 0.1 g pentobarbital, and sometimes 0.025 g meperidine.

A sterile solution of isotonic saline saturated with dissolved hydrogen (hereafter referred to as H_2-saline) was prepared by passing H_2 from a standard gas cylinder through a sterile filter and bubbling it through an inverted infusion bottle of isotonic saline for 15–20 min. A gear-driven pump was then used to infuse the solution selectively into the bypass graft at a rate of 3.6, 7.2, or 18 ml/min for a minimum of 7 min and usually for 10–15 min. For studies at the time of operation, the graft was punctured directly with a 25 gauge needle. For postoperative studies, the graft was catheterized selectively with a catheter inserted percutaneously into a femoral artery. The postoperative catheterizations were facilitated by the placement at surgery of silver clips marking the takeoff of the venous grafts from the aorta. 2.0-ml samples of coronary venous blood were drawn for gas chromatographic analysis of blood H_2 concentration (5) before H_2 infusion was begun,[4] during the last few minutes of H_2 infusion and for 15–20 min thereafter. The samples were obtained through a catheter inserted at least 2 cm beyond the ostium of the coronary sinus (to avoid right atrial admixture) (2). At the time of operation, the catheter was inserted through a right atrial purse-string suture used for a venous drainage catheter during cardiopulmonary bypass. In the postoperative studies a No. 7 or 8 Sones catheter was inserted through a venotomy in a superficial elbow or forearm vein. Three points about the protocol are noteworthy.

(*a*) The relatively long periods of test gas delivery were intended to allow areas within the revascularized segment having different F/V to achieve the same test gas concentration, i.e., to become saturated evenly. (*b*) Arterial H_2 concentrations became negligible as soon as H_2 infusion was discontinued. The H_2 concentration of blood leaving the coronary venous system was reduced by $\sim 95\%$ as it mixed with the remainder of systemic venous return. In addition, as mixed venous blood passed through the lungs, its H_2 concentration was reduced by another 95–98% because of the low solubility of H_2 in blood (5). Thus, systemic arterial H_2 concentration was negligible throughout desaturation.[5] (*c*) Venous H_2 concentrations during desaturation were resolved to 1–3% of the levels present at the onset of desaturation. This involved 15- to 20-min periods of observation and a specially designed thermal conductivity gas chromatograph (5) for the analysis of blood H_2 concentration.

"Over-all" or "average" flow for the entire revascularized segment was calculated by dividing the difference in venous H_2 concentration between the onset and termination of desaturation by the area under the linearly plotted venous desaturation curve. H_2 concentrations were expressed in arbitrary units of chromatographic peak height, with the venous concentration at the onset of desaturation always assigned a value of 100 U. The tissue-blood partition coefficient for H_2 and myocardial specific gravity were both taken as 1.0. Heterogeneity of flow within the revascularized segment was evaluated by examining the contour of the venous desaturation curve after it had been replotted semilogarithmically against time.

In 9 of the 10 studies performed at operation, an electromagnetic flowmeter[6] was used to measure total flow through the bypass graft. Zero flow levels were obtained by temporarily occluding the graft. A short period of reactive hyperemia was usually seen before flow stabilized at the level used for the subsequent calculation of mass of the revascularized segment. The latter was obtained by dividing total flow measured electromagnetically (milliliter per minute) by average F/V for the entire segment (milliliter per minute per 100 g).

RESULTS

Findings were generally similar in the operative and postoperative studies and are shown in Table I and Figs. 1–3. Average F/V for the entire series ranged from 32 to 117 ml/min per 100 g and averaged 67 ± 21 (SD) ml/min per 100 g. When plotted semilogarithmically, all desaturation curves clearly deviated from a single exponential (Fig. 2). Values of revascularized segment mass ranged from 46 to 155 g and averaged 88 ± 38 g. The electromagnetic flows involved in these

[2] Picker X-Ray Corp., White Plains, N. Y.

[3] Bypass graft surgery for coronary artery obstruction at the Buffalo General Hospital routinely includes an attempt to visualize the graft arteriographically before the patient leaves the hospital after surgery. Of our first 49 patients operated on, 47 survived and 45 were restudied angiographically.

[4] Small traces of H_2 are sometimes present in coronary venous blood. In such cases, an appropriate "blank correction" is applied to samples drawn during H_2 saturation and desaturation.

[5] Systemic arterial blood samples were actually drawn during three desaturation studies and showed no trace of H_2.

[6] Model 610, Biotronex Laboratory, Inc., Silver Spring, Md.

Table I

Bypass Graft Flow in Operative and Postoperative Studies

	Age	Site of bypass graft studied	ΔCcs_{H_2}*	Area under linear desaturation curve	F/V	EMF	Calculated mass of perfused segment
	yr		*arbitrary units*	*arbitrary units × min*	*ml/min per 100 g*	*ml/min*	*g*
Operative series							
S. Y.	62	LAD	>99	153	65	100	155
G. C.	43	RCA	>99	143	70	60	86
		LAD	>99	158	63	50	79
R. McG.	45	RCA	98	182	54	25	46
		LAD	99	153	65	40	62
W. V.	59	LAD	>99	141	71	80	113
T. H.	60	RCA	>99	93.0	108	60	56
		LAD	>99	85.5	117	170	145
N. R.	51	LAD	98	288	34	—	—
E. P.	57	LAD and LC‡	>99	132	76	40	53
Mean ±SD	54 ±7				72 ±23	69 ±41	88 ±38
Postoperative series							
T. K.	49	RCA	97	152	64	—	—
C. B.	45	LAD	>99	227	44	—	—
R. W.	54	RCA	97	303	32	—	—
J. R.	57	LAD	>99	181	55	—	—
R. D.	39	LAD	>99	127	79	—	—
H. G.	55	LAD	>99	158	63	—	—
F. T.	61	LAD	99	153	65	—	—
S. Y.	62	LAD	>99	101	99	—	—
R. McG.	45	RCA	99	168	59	—	—
L. C.§	41	LAD	99	160	62	—	—
A. R.	37	RCA	>99	194	52	—	—
Mean ±SD	50 ±8				61 ±17		

* ΔCcs_{H_2}, change in coronary sinus H_2 concentration between onset and termination of desaturation (for purposes of calculation, changes >99 arbitrary units were taken as 100 arbitrary units); F/V, flow per unit volume; EMF, electromagnetic flow; RCA, right coronary artery; LAD, left anterior descending coronary artery; LC, left circumflex coronary artery.

‡ This was a Y graft connected to both LAD and LC. H_2 and EMF measurements were made upstream to the point of graft bifurcation.

§We are indebted to Drs. Herman L. Falsetti and Murray N. Andersen for permission to include the data from this patient.

calculations varied from 25 to 170 ml/min and averaged 69 ±41 ml/min.

DISCUSSION

Most problems in the estimation of coronary blood flow in disease states relate to the need to adhere strictly to methodological precautions when flow is distributed heterogeneously. These precautions have been described in detail in previous publications (2–4, 6). However, two deserve special emphasis.

(*a*) For most methods of calculation commonly used in measurements of coronary flow, the preliminary period of test gas saturation must be adequate to achieve the same gas concentration in areas of low flow as in areas of normal flow. (*b*) Measurements during desaturation must be continued for a sufficiently long time, with sufficiently sensitive analytical techniques, to allow for the accurate quantitation of prolonged venous-arterial differences originating in areas of low flow. In the present studies, the prolonged periods of test gas infusion and the resolution of desaturation curves through two logarithmic cycles were intended to meet these requirements. It appears unlikely that techniques employing bolus injection of indicator and resolution of a desaturation curve through a single logarithmic cycle would be adequate. The finding of consistently non-

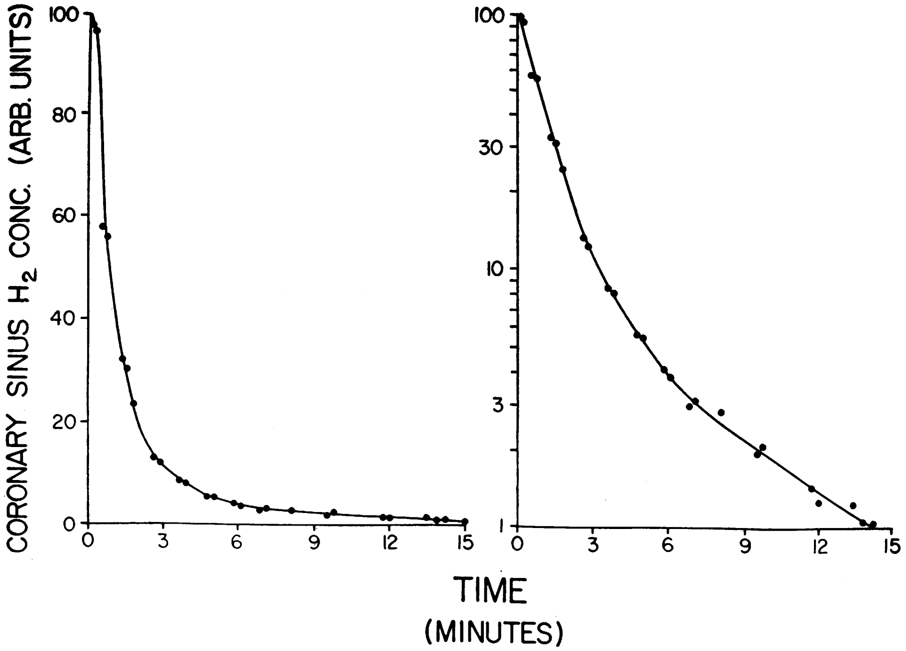

FIGURE 1 Coronary venous H_2 desaturation at surgery in R. McG. after 11 min infusion into aorta-to-left anterior descending graft. Average F/V calculated from the linear plot on the left is 65 ml/min per 100 g. The nonlinear semilogarithmic plot on the right indicates heterogeneity of flow within the revascularized segment.

linear desaturation curves on semilogarithmic plots (Fig. 2) indicates that flow is never uniform within a revascularized segment. This is not surprising in view of evidence that coronary flow shows some heterogeneity in healthy mongrel dogs and normal human adults (2). The degree of heterogeneity is known to be increased in the presence of coronary artery disease (2) and possible explanations for "persistent" heterogeneity after revascu-

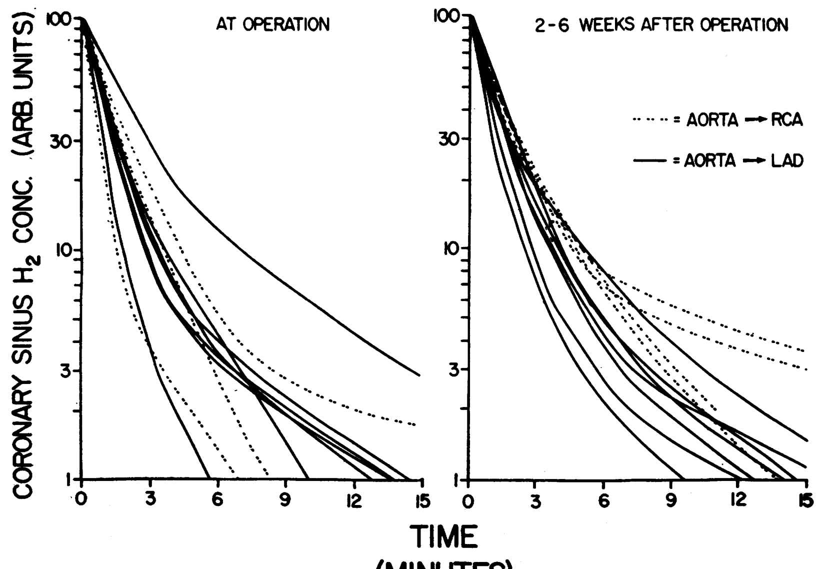

FIGURE 2 Semilogarithmic plots of initial 15 min of H_2 desaturation in all 21 studies. RCA, right coronary artery, LAD, left anterior descending coronary artery.

larization would have to include coronary artery disease distal to the site of graft implantation and myocardial fibrosis. The relative perfusion of endocardial and epicardial regions of the ventricle is also uncertain and may vary in different physiological situations and disease states. In any event, the present study does not allow a conclusion about the anatomical basis of the observed heterogeneity. The report by Smith, Gorlin, Herman, Taylor, and Collins of an increased rate of indicator clearance when an occluded bypass graft is opened suggests that the degree of heterogeneity in a revascularized segment is reduced by the graft (7). Since the present study does not contain duplicate observations in individual patients, and since only two patients were studied both at and after operation, the study also does not allow a systematic comparison of flows at surgery and postoperatively in individual patients.

Practical methods for characterizing heterogeneity of perfusion in a quantitative manner are of interest but are still early in their development. One arbitrary and admittedly crude approach is to treat the individual curves in Fig. 2 by curve-peeling techniques to define equivalent two-compartment models. When such models are constructed for these curves, the more rapidly perfused compartment occupies 62 ±8% (SD) of the revascularized segment and has a F/V of 93 ±30 ml/min per 100 g. The more slowly perfused compartment has a F/V of 19 ±10 ml/min per 100 g. While such an analysis is unrealistic from an anatomic point of view, it does emphasize the relatively wide range of F/V within the revascularized segment. The majority of the segment has a F/V within the accepted range of normal, but there remain areas in which F/V is reduced significantly.

The calculation of segment mass also requires comment. Areas of myocardium supplied by a bypass graft are potentially also perfused through the same route as before the graft was inserted, i.e., through the coronary artery to which the graft has been attached. This additional flow is not included in the electromagnetic measurement of total flow and could lead to an underestimate of segment mass. However, several factors suggest that the magnitude of this error is small.

(*a*) The vessel to which the graft is attached is always one which is severely narrowed between its origin and the point of attachment of the graft, so that its effective cross-section is reduced severely. The graft, on the other hand, is larger in cross-section than even the normal coronary artery. Because the end-to-side anastomosis is made with a diagonal cut across the end of the vein, the anastomotic site is wide and offers no appreciable impedance to flow. The large majority of flow is therefore expected to come through the larger unobstructed channel. This reasoning seems especially plausible in view of the report from Gorlin of 50–70 mm Hg

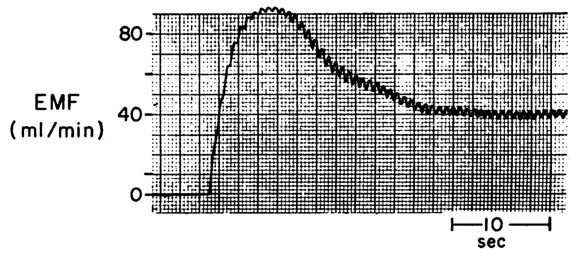

FIGURE 3 Electromagnetic flow measurement for aorta-to-left anterior descending graft in R. McG. at the time of surgery. A short period of reactive hyperemia follows release of the occluding clamp used to determine zero flow.

gradients across the narrowed coronary artery (8). (*b*) At the time of postoperative arteriography, bidirectional flow was visible in the diseased coronary artery in over 80% of cases. The presence of bidirectional flow may imply a significant gradient across the stenotic region. (*c*) Reactive hyperemia was noted after brief occlusion of the graft to obtain an electromagnetic zero flow level in 7 of 9 cases. The presence of reactive hyperemia may imply that flow through the diseased coronary artery is too small to prevent ischemia at rest.[7]

Finally, it should be noted that values for calculated mass really represent the volumes of distribution of the indicator used to make the measurement (6).

The electromagnetic flowmeter values in the present study are also of interest in relation to those previously reported by other groups. Johnson, Flemma, and Lepley (9) reported an average flow of 63 ml/min in a large series of bypass grafts, with flows as high as 185 ml/min in a graft to an anterior descending coronary artery and 155 ml/min in a graft to a right coronary artery. Flows were generally greater in grafts with bidirectional flow than in grafts with unidirectional flow. Our values (average 69 ml/min, range 25–170 ml/min) seem comparable.

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[7] Any additional statement about the meaning of reactive hyperemia in terms of "improved flow reserve" would require knowledge about the status of collateral coronary circulation before and after the graft is inserted.

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