Coronary Arterial Bypass Grafts

George E. Green, M.D., Simon H. Stertzer, M.D., and Edmund H. Reppert, M.D.

Postmortem examination of the hearts of patients with atherosclerotic coronary occlusive disease has shown that the arteries of the distal third of the coronary tree are usually not affected by the occlusive process [7, 12, 13, 16, 17, 22]. This is particularly true of the left coronary artery [12]. The arteries of the distal third measure 1 to 2 mm. in external diameter. Blumgart et al. [4] expressed the opinion that bypass grafting to such arteries "would offer important relief" to patients with coronary occlusive disease. This report evaluates the feasibility of bypass grafting to coronary segments of 1 mm. in diameter.

METHODS AND MATERIALS

Bypass grafting was performed in dogs weighing 6 to 25 kg. (most were between 12 and 18 kg.) by suture anastomosis of the distal end of the totally mobilized internal mammary artery to a distal segment of the left anterior descending artery. The internal mammary artery at the site of anastomosis measured 1.5 mm. The segment of the left anterior descending artery to which it was anastomosed measured 1.0 mm. All anastomoses were constructed with a continuous suture of 9-0 monofilament nylon under 16× magnification of an operating microscope.

Performance of the anastomosis was evaluated under three sets of conditions. Anastomoses were constructed in isolated coronary segments with the heart beating and, using cardiopulmonary bypass, with the vented heart fibrillating. Neither of these techniques afforded optimal conditions for anastomosis.

Optimal conditions were obtained by using cardiopulmonary bypass, fibrillating the vented heart, cross-clamping the aorta, and washing all blood from the coronary system by flushing the aortic root with cold Ringer's solution. This technique rapidly quieted the heart and avoided the necessity for a tedious and hazardous dissection to isolate a distal segment of the coronary artery. With all blood flushed from the coronary system it was merely necessary to incise a distal coronary segment and then to perform suture anastomosis.

Various intervals of aortic cross-clamping were evaluated; 20 minutes was found to be safe. If anastomosis was not completed within 20 minutes, the arteriotomy was tamponaded with a finger and the root of the aorta unclamped for 5 minutes. Following completion of the anastomosis, the left anterior descending

From the Departments of Surgery and Medicine, New York University Medical Center, New York, N.Y.

This work was supported in part by Grant HE 11086-02 from the National Heart Institute of the National Institutes of Health, U.S. Public Health Service.

Presented at the Fourth Annual Meeting of The Society of Thoracic Surgeons, New Orleans, La., Jan. 29–31, 1968.

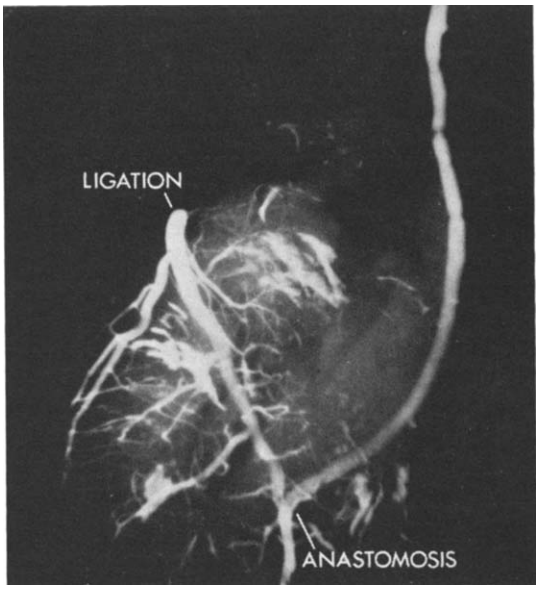

FIG. 1. Typical postmortem barium angiogram.

coronary artery was carefully dissected at its origin from the main coronary artery and, in all but 1 case, ligated.

The techniques of perfusion varied. Best results were obtained with non-blood prime of low-prime oxygenators. In these cases no homologous blood transfusion was needed. Optimal heparinization seemed to be 4 mg. per kilogram of body weight. This was neutralized after bypass with an equal amount of protamine. Both sodium pentobarbital and halothane were evaluated as anesthetic agents; the latter was greatly superior if care was taken to administer the minimal amount, especially following bypass.

In selected cases flow studies were performed with a Statham square-wave electromagnetic flowmeter. The flowmeter was applied to the completely mobilized internal mammary artery as it lay in situ, after anastomosis, immediately after proximal ligation of the left anterior descending coronary artery, and then 3 weeks and 6 months following initial operation.

Electrocardiographic monitoring was performed in the majority of dogs during operation.

Six dogs were studied by cineangiography at intervals from 4 to 7 months postoperatively. Four dogs succumbed between 2 and 4 weeks after operation, and their hearts were subjected to histological examination. All dogs that died, except those reserved for histological sectioning, were studied postmortem by barium angiography (Fig. 1) to assess the patency of the anastomoses.

RESULTS

Forty-two dogs were operated (Table 1). All early deaths occurred in the first 20 dogs. Ten dogs died the day of surgery. Inadequate bypass, due to low blood flow, caused 3 deaths, and overdosage of halothane caused 3 deaths. It was striking that tolerance to halothane was markedly reduced following bypass. Excessive myocardial anoxia due to interruption of coronary flow for more than 25 minutes resulted in inability to defibrillate the heart in 2 dogs. A systematic study of canine tolerance to anoxia was not done. However, return of heart function

TABLE 1. SURVIVAL TIME AND CAUSE OF DEATH AFTER CORONARY ARTERIAL BYPASS GRAFT IN 42 DOGS

No. of Dogs	Survival Time After Cardiopulmonary Bypass	Cause of Death
10	0–12 hr.	Inadequate bypass (3 dogs), halothane overdose (3 dogs), excessive myocardial anoxia (2 dogs), air embolism (2 dogs)
9	12–24 hr.	Hemothorax
13	1– 4 days	Respiratory insufficiency
2[a]	2 wk.	Wound infection
2[a]	4 wk.	Pneumonia
6	4– 8 mo.	Surviving

[a]Hearts examined by serial histological sectioning (Histology Service, Inc., Philadelphia, Pa.).

was satisfactory in all animals that had aortic cross-clamping for 20 consecutive minutes, except in those dogs that suffered air embolism, as noted below. Moreover, 4 dogs that had periods of aortic cross-clamping for between 15 and 20 consecutive minutes died between 2 and 4 weeks postoperatively, and their hearts were subsequently examined by serial histological section; no pertinent myocardial abnormality was present in these dogs.

Air embolism to the coronaries resulted in inability to defibrillate the hearts in 2 instances. Nine dogs died 12 to 24 hours following surgery of slowly progressive hemothorax. The bleeding originated from either the site of coronary mobilization, when this technique was employed, or the site of anastomosis. Thirteen dogs died of respiratory insufficiency due to severe pulmonary atelectasis and congestion. These deaths occurred from 1 to 4 days following surgery, and were almost entirely limited to those dogs in which the disc oxygenator primed with homologous blood was used. Two dogs were sacrificed because of wound sepsis 2 weeks following surgery. Two dogs died of pneumonia a month after surgery.

Postmortem angiography (Fig. 1) was performed in all cases through the internal mammary graft and demonstrated the patency of each anastomosis. None were occluded.

Six dogs survived more than 3 months and were studied by selective cineangiography. The anastomoses were proved to be patent in all (Figs. 2–4). The density of the dye in both the arterial and the venous phases suggested a very large flow. This was borne out by flow studies.

Electromagnetic flow probes were placed around the completely mobilized internal mammary artery while it was in situ. Mean flow (in 5 dogs) averaged 10 ml. per minute. When the vessel was divided at its epigastric termination and allowed to bleed into a beaker, mean flow averaged 40 ml. per minute. Following anastomosis to the distal coronary, flow through the internal mammary artery averaged 15 ml. per minute. This was taken to imply that the peripheral coronary resistance was less than the epigastric resistance. When peripheral coronary resistance was further reduced by proximal ligation of the anterior descending artery, mean flow through the internal mammary artery increased to an average mean of 30 ml. per minute. One dog weighing 25 kg. had a mean flow of 90 ml. per minute (Fig. 5) 6 months postoperatively. Stimulation with 200 μg. of epinephrine intravenously caused the mean flow to increase to 116 ml. per minute.

Proximal ligation of the left anterior descending artery was omitted in one instance in order to evaluate the fate of the graft in the absence of "demand."

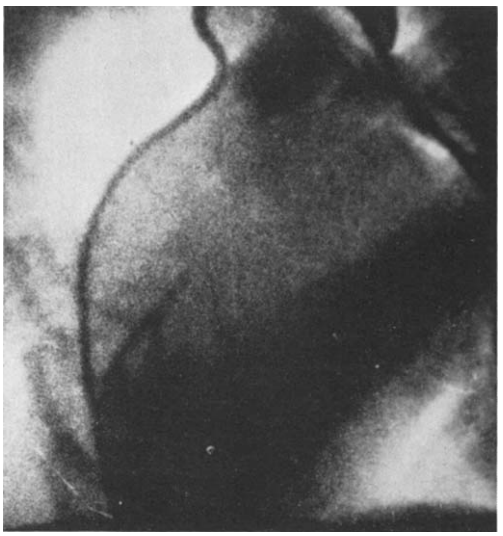

FIG. 2. Enlargement of one frame of cineangiogram of dog "F" 3 weeks postoperatively.

Cineangiography 5 months after anastomosis revealed the graft to be patent. However, the internal mammary artery appeared not to have hypertrophied, as did the other internal mammary arteries. With gentle hand injection, capillary stain was evident in the myocardium. With forceful hand injection, dye was refluxed one-third of the way up the anterior descending artery.

Electrocardiographic monitoring at the time of surgery usually revealed no ST-segment or T-wave changes following proximal ligation. In several cases, however, such changes did occur. In these the coronary segment to which the internal mammary artery was anastomosed was less than one-third of the diameter of the proximal coronary at its site of ligation. In 1 of these cases there was postoperative electrocardiographic evidence of myocardial infarction. This dog is surviving with a patent graft.

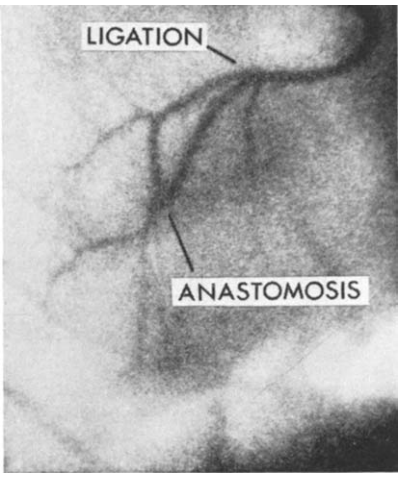

FIG. 3. Enlargement of one frame of cineangiogram of dog "D" 6 months postoperatively.

FIG. 4. Enlargement of one frame of cineangiogram of dog "M" 6 months postoperatively.

Electrocardiographic monitoring at the time of cineangiography revealed severe T-wave inversions concurrent with injection. Ventricular fibrillation occurred in one instance.

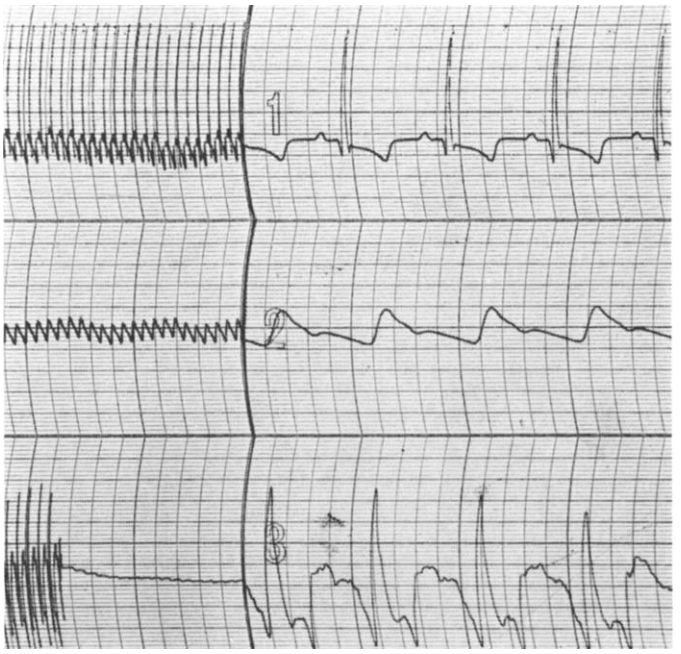

FIG. 5. Flow study of the internal mammary artery graft of dog "M." From top to bottom the tracings are: lead II of electrocardiograph, aortic arch blood pressure (125/80 mm. Hg), and mean flow through the internal mammary artery (90 ml./min.). Peak flow was recorded to be 161 ml./min.

DISCUSSION

There is considerable evidence that indirect coronary artery surgery, notably, implantation of the internal mammary artery into the myocardium, can, after an interval of several months, augment perfusion of the ischemic myocardium [10, 18, 20, 21]. However, it is becoming clear that not all patients will be significantly helped by an implant procedure. Taylor and Gorlin [20], on the basis of preoperative and postoperative study of cineangiograms, lactate metabolism, and blood flow estimations, stated that the ideal candidate should have demonstrable collateral flow to the ischemic area preoperatively. This contention is supported by the data of Fergusson et al. [10], which similarly indicate that almost 90% of patients with cineangiographically demonstrable preoperative collateral flow to the ischemic area will have coronary artery filling from an implant, whereas less than 40% of patients without such preoperative collateral flow will have demonstrable coronary filling following an implant. Nevertheless, a very substantial proportion of coronary patients lack angiographically demonstrable collaterals, and these are the same patients who are most prone to sudden death [13]. A direct coronary operation that achieves immediate increase in blood flow would be best for such patients.

The predominant surgical attempt to immediately augment blood flow to the ischemic heart has been endarterectomy [1, 5, 6, 8, 11] or endarterotomy [9]. However, the results of these operations on the artery of most importance, the left coronary [7], have generally been unsuccessful. Operative mortality has exceeded 50% [9], and reocclusion or restenosis in survivors has exceeded 50% [6, 8, 11]. Most occlusions are located so far proximally that they are in areas of the left coronary artery that are obscured by the overlying pulmonary artery. Poor surgical exposure makes successful endarterectomy unlikely. The technique of gas endarterectomy has not yet proved to be a significant adjunct [15]. Furthermore, when endarterectomy is technically successful, an uncontrollable healing process is initiated. The thickness of fibrin deposition on the endarterectomized segment is unpredictable, whereas a thickness of neointima which is insignificant in the femoral artery may occlude many coronary segments. Dilley et al. [8] attributed most of their late failures to excessive deposition of neointima. Moreover, the neointima seems more vulnerable to the atherosclerotic process than the original arterial wall [19]. In contrast to endarterectomy, bypass grafting of the internal mammary artery to distal (1 to 2 mm.) segments of the coronary tree coapts normal arterial walls. Therefore, long-term patency is to be expected. Such grafts can immediately bring copious amounts of blood to where it is needed, the hypertrophied intercommunicating tree of distribution [2, 3, 14, 23]. There is no technical barrier to the successful performance of such grafts.

SUMMARY

The pathological anatomy of coronary atherosclerosis suggests that arterial bypass grafting to distal coronary segments (1 to 2 mm. external diameter) would offer important relief of myocardial ischemia. Evaluation of 42 grafts in dogs establishes that such grafts can be made with consistent patency. High magnification (16×) and cardioplegia are essential elements of the surgical technique.

ADDENDUM

On February 29 and March 12, 1968, this technique of bypass grafting was applied clinically, with success. However, cross-clamping of the aorta was not necessary clinically because in humans a segment of coronary artery can be found that is sufficiently free of myocardial branches to be isolated between temporary occluding ligatures.

REFERENCES

1. Allison, P. R. Thrombo-endarterectomy and its application to coronary artery disease. *Brit. Med. J.* 1:1641, 1962.
2. Baroldi, G., Mantero, O., and Scomazzoni, G. The collaterals of the coronary arteries in normal and pathologic hearts. *Circ. Res.* 4:223, 1956.
3. Blumgart, H. L., Schlesinger, M. J., and Davis, D. Studies on the relation of the clinical manifestations of angina pectoris, coronary thrombosis, and myocardial infarction to the pathologic findings. *Amer. Heart J.* 19:1, 1940.
4. Blumgart, H. L., Zoll, P. M., and Kurland, G. Discussion of direct relief of coronary occlusion: The anatomic pathologic problem. *A.M.A. Arch. Intern. Med.* 104:862, 1959.
5. Cannon, J. A., Longmire, W. P., Jr., and Kattus, A. A. Considerations of the rationale and technique of coronary artery endarterectomy for angina pectoris. *Surgery* 46:197, 1959.
6. Crafoord, C. Some aspects of surgery for coronary disease. *Surgery* 49:215, 1961.
7. Crawford, T., Dexter, D., and Teare, R. D. Coronary artery pathology in sudden death from myocardial ischemia. *Lancet* 1:181, 1961.
8. Dilley, R. B., Cannon, J. A., Kattus, A. A., MacAlpin, R. N., and Longmire, W. P., Jr. The treatment of coronary occlusive disease by endarterectomy. *J. Thorac. Cardiov. Surg.* 50:511, 1965.
9. Effler, D. B., Sones, F. M., Jr., Favaloro, R., and Groves, L. K. Coronary endarterotomy with patch-graft reconstruction. *Ann. Surg.* 162:590, 1965.
10. Fergusson, D. J., Shirey, E. K., Sheldon, W. C., Effler, D. B., and Sones, F. M., Jr. Left internal mammary artery implant operation: Postoperative assessment. (Abstract.) *Circulation* 36(Suppl. II):107, 1967.
11. Kattus, A. A., Longmire, W. P., Jr., Cannon, J. A., Dilley, R. B., and MacAlpin, R. N. Results of coronary endarterectomy for angina pectoris with angiographic restudy of survivors. *Circulation* 30(Suppl. II):113, 1964.
12. Lyons, M. Personal communication, 1967.
13. Miale, J. B., and Bledsoe, A. Pathologic anatomy of coronary heart disease. *A.M.A. Arch. Path.* 56:577, 1953.
14. Pitt, B. Interarterial coronary anastomosis: Occurrence in normal hearts and in certain pathologic conditions. *Circulation* 20:816, 1959.

15. Sawyer, P. N., Kaplett, M., Sobel, S., Karlson, K. E., Studkey, J., Wechsler, B. M., Summers, D. N., and Dennis, C. Experimental and clinical experiences with coronary gas endarterectomy. *Arch. Surg.* (Chicago) 95:737, 1967.
16. Schlesinger, M. J. Relation of anatomic pattern to pathologic conditions of coronary arteries. *Arch. Path.* 30:403, 1940.
17. Schlesinger, M. J., and Zoll, P. M. Incidence and localization of coronary artery occlusions. *Arch. Path.* 32:178, 1941.
18. Sewell, W. H. Results of 122 mammary pedicle implantations for angina pectoris. *Ann. Thorac. Surg.* 2:17, 1966.
19. Szilagyi, D. E., Smith, R. F., and Whitney, D. G. The durability of aortoiliac endarterectomy. *Arch. Surg.* (Chicago) 89:827, 1964.
20. Taylor, W. J., and Gorlin, R. Objective criteria for internal mammary artery implantation. *Ann. Thorac. Surg.* 4:143, 1967.
21. Vineberg, A. M. Experimental background of myocardial revascularization by internal mammary implantation and supplementary technics with its clinical application in 125 patients. *Ann. Surg.* 159:185, 1964.
22. White, N. K., Edwards, J. E., and Thomas, J. D. The relationship of the degree of coronary atherosclerosis with age, in men. *Circulation* 1:645, 1950.
23. Zoll, P. M., Wessler, S., and Schlesinger, M. J. Interarterial coronary anastomoses in the human heart, with particular reference to anemia and relative cardiac anoxia. *Circulation* 4:797, 1951.

NOTICE FROM THE SOCIETY OF THORACIC SURGEONS

The Second National Conference on Prosthetic Heart Valves, sponsored by The Society of Thoracic Surgeons, will be held at the Century Plaza Hotel, Los Angeles, on May 30, 31, and June 1.

This conference is made possible by grant supports from the National Institutes of Health and the City of Hope Medical Center. The conference will be open to all interested in this aspect of thoracic surgery.

There will be no registration fee. Programs will be mailed automatically to the members of the Society and to members of the American Association for Thoracic Surgery; others may obtain them from Francis X. Byron, M.D., City of Hope Medical Center, 1500 East Duarte Road, Duarte, Calif. 91010.