Myocardial preservation

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Despite advances in anesthetic and surgical management, a substantial number of patients still sustain some degree of myocardial damage during cardiac operations designed to repair their hearts. Although myocardial necrosis can occur at any time during the perioperative period, damage most often results from inadequate myocardial preservation during cardiopulmonary bypass.[1] The purpose of this publication is to discuss first, some of the mechanisms and manifestations of myocardial damage during cardiopulmonary bypass; and second, some interventions that can be made during the bypass interval to protect jeopardized myocardium.

Although the precise mechanism of cell death remains controversial, the process is probably initiated by a period of ischemia. If the ischemia is prolonged, depletion of cellular glycogen, high energy phosphate and other metabolites occurs followed by cell swelling and membrane disruption.[2] Structural damage may be detected at autopsy or clinically by electrocardiography, and enzyme and radionuclide imaging techniques. Structural damage predisposes to functional impairment manifest clinically as low cardiac output with the need for inotropic or mechanical support. Persistent ventricular arrhythmias may be a subtle manifestation of

myocardial damage. A not so subtle but fortunately uncommon sign of damage is ischemic contracture ("stone heart").

It is not clear whether impaired cardiac function always indicates that structural damage has occurred. It may be possible for ischemia to induce temporary reversible dysfunction of the subcellular mechanisms of energy production or excitation contraction coupling or both without permanent structural damage. Further investigation in this area is needed. Data presently available suggest that *persistently* low cardiac output after cardiopulmonary bypass is usually accompanied by marked myocardial necrosis.[3]

Events during cardiopulmonary bypass that predispose to ischemia and subsequent structural and functional impairment include the following: (1) ventricular fibrillation, (2) inadequate myocardial perfusion, (3) ventricular distention, (4) ventricular collapse, (5) coronary embolism (gas or particulate), (6) inotropic support during weaning from cardiopulmonary bypass, and (7) aortic cross-clamping. These factors may cause ischemic damage secondary to either decreased myocardial oxygen supply, increased oxygen consumption, or both. The presence of one or more of these events in combination further potentiates myocardial damage. For example, the hypertrophied, distended, fibrillating ventricle with a low perfusion gradient would be particularly susceptible to damage. Whether or not exposure to these causative factors indeed results in subsequent injury depends on myocardial vulnerability, duration of exposure, and adequacy of protective measures. Myocardial damage occurs more often when vulnerability is high (hypertrophied left ventricle), duration of exposure prolonged, and protective measures inadequate.

The goals of management are first to prevent or minimize the duration of exposure to causative factors, and second, to provide maximum myocardial protection during unavoidable or iatrogenically induced ischemia. How these goals can be achieved in clinical practice, causative events, and corrective measures are discussed.

Ventricular fibrillation

Hottenrott et al[4] have shown that ventricular fibrillation during cardiopulmonary bypass may result in impaired subendocardial blood flow and increased myocardial oxygen consumption. Factors potentiating these deleterious effects include prolonged, high-frequency fibrillation, ventricular distention, low myocardial perfusion gradient, and ventricular hypertrophy. Premature ventricular fibrillation in the prerepair interval can be controlled by minimizing manipulation of the heart, avoiding rapid myocardial cooling with perfusate or external cooling solutions and pretreatment with propranolol.[5–7] When fibrillation does occur, aortic cross-clamping and the infusion of cardioplegic solution should be done as quickly as possible. Following repair, fibrillation is controlled by cardioversion, increasing myocardial perfusion pressure, optimizing perfusate temperature, pH, potassium and oxygen content, and rarely by the administration of antiarrhythmics. Persistent fibrillation suggests inadequate repair, coronary embolism and/or substantial myocardial damage.

Inadequate myocardial perfusion

The myocardial perfusion pressure gradient during nonpulsatile cardiopulmonary bypass is proportional to the aortic blood pressure minus coronary sinus or transmitted left ventricular in-

tracavitary pressure. Clinically, this is approximated by mean radial artery pressure minus mean left atrial pressure.

The optimal perfusion pressure gradient varies with conditions. A higher gradient is required to insure adequate perfusion of the concentrically hypertrophied left ventricle.[4–6] The myocardial perfusion gradient can be increased during cardiopulmonary bypass by increasing pump flow, the judicious use of a vasopressor, and left ventricular decompression.

Ventricular distension

Distention of the heart raises myocardial oxygen consumption by increasing wall tension at a time when the perfusion gradient is reduced secondary to increased intracoronary pressure transmitted to the subendocardium. Ventricular distention can be controlled mechanically with a vent or pharmacologically with a vasodilator.

Ventricular collapse

Changes in myocardial compressive forces and ventricular geometry associated with the empty beating heart predispose to subendocardial ischemia. This is particularly true with small-chambered concentrically hypertrophied hearts of aortic stenosis.[8]

Coronary embolism

Coronary embolism, either gas or particulate, impairs perfusion and predisposes to fibrillation. Preventive measures include the venting of vein grafts and evacuation of intracardiac air.

Inotropic agents during weaning from cardiopulmonary bypass

The prolonged use of potent inotropic agents in high doses may cause disproportionate increases in myocardial oxygen demand relative to supply. During weaning from cardiopulmonary bypass every effort should be made to optimize heart rate, preload and afterload, before resorting to the use of inotropic agents to enhance contractility. Persistent low cardiac output, despite the administration of inotropic agents, suggests the need for mechanical support.

Aortic cross-clamping

Most surgeons agree that it is extremely difficult to do a precise repair with the heart beating and bleeding. Therefore, to improve exposure, myocardial ischemia is commonly induced by aortic cross-clamping. If the heart is intentionally rendered ischemic by aortic cross-clamping then interventions must be made to protect the myocardium during the nonperfusion period. Methods of myocardial protection during aortic cross-clamping vary from institution to institution, but all protocols do or should include some element of myocardial hypothermia. The experimental evidence is clear that lowering myocardial temperature results in less cell death and better function at the end of the ischemic period.[9]

More recently there has been a revival of the use of so-called cardioplegic solutions designed to produce immediate and sustained cessation of all electrical and mechanical cardiac activity. There is no agreement regarding the composition of the ideal solution. The principles that determine the clinical composition of any cardioplegic solution have been recently reviewed by Buckberg.[10] In the United States the most common agent used to produce electrical and mechanical quiescence is potassium in concentrations from 20 to 40 mEq/L. Whether other agents such as procaine, lidocaine, calcium antagonists, steroids, and mannitol provide protection remains to be documented.

Supplemental measures to maintain myocardial cooling and prevent the accelerated washout of cardioplegic solution are central to the success of the technique. This is especially true in patients with severe proximal coronary artery lesions and extensive aortocoronary collateral flow. The need for and effectiveness of additional interventions designed to provide myocardial quiescence and hypothermia is best determined by the direct measurement of myocardial electrical activity and temperature. The use of a myocardial thermistor electrogram probe provides a measurable end point for assessing the adequacy of myocardial protection during cardiopulmonary bypass. The probe is inserted to a depth of 1 cm into the septal myocardium. In clinical practice, site selection may be modified by the presence of septal scarring secondary to previous infarction. Monitoring the electrogram facilitates probe placement in viable myocardium rather than scar tissue. Both the septal myocardium temperature and electrogram are displayed continuously on a digital readout and oscilloscope. *Figure 1* shows a typical septal electrogram recorded simultaneously with the aortic root infusion of cold potassium cardioplegic solution. Note the rapid cessation of electrical activity associated with a fall in septal temperature. *Figure 2* illustrates changes in myocardial, nasopharyngeal, and perfusate temperatures versus time during a myocardial revascularization procedure. Initially there is a gradual decline in myocardial temperature with perfusate cooling and the subsequent rapid fall with aortic root infusion of cold cardioplegic solution. Failure to observe the increasing rate of cooling suggests improper thermistor placement, inadequate cardioplegic infusion rate, aortic insufficiency, or severe proximal coronary stenosis. Recognition of these conditions leads to interventions designed to insure optimal myocardial preservation such as repositioning the thermistor, increasing infusion rate and/or volume, infusing directly into the coronaries or vein grafts, and lowering perfusate temperature. A rapid rise in myocardial temperature after initial cooling suggests any of the following: thermistor displacement, nonocclusive cross-clamp, extensive aortocoronary collateral flow, or inadequate cardiac decompression. Again, awareness of these conditions results in corrective interventions, such as repositioning of the probe, tightening the cross-clamp, lowering perfusate temperature and flow, use of external cooling, placement of a left ventricular vent, and/or reinfusion of cardioplegic solution.

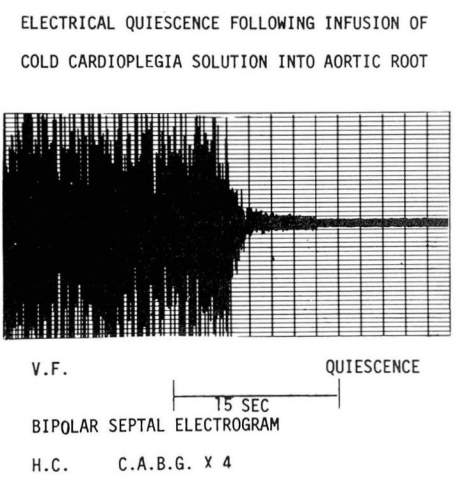

Fig. 1. Continuous tracing of myocardial septal electrogram during infusion of hypothermic (7 C) cardioplegic solution into the aortic root. Note the rapid conversion from ventricular fibrillation to electrical quiescence.

Following release of the aortic cross-clamp, there is a rapid rise in septal temperature (*Fig. 2*). Electrical and mechanical activity usually does not return for 4 to 5 minutes. This interval of persistent cardioplegia during initial reper-

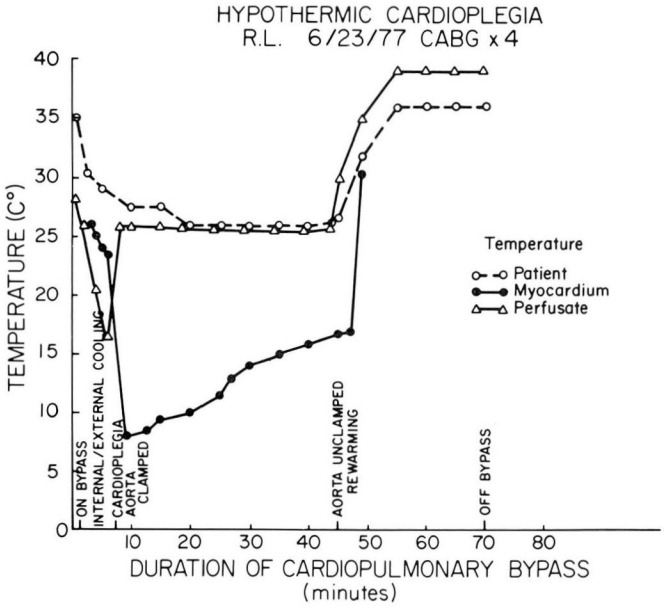

Fig. 2. Simultaneous plots of nasopharyngeal, septal myocardial, and perfusate temperature during cardiopulmonary bypass.

fusion is beneficial in terms of replenishing depleted metabolites before mechanical contraction. Follette et al[11] have emphasized the importance of manipulating perfusate temperature, composition, and flow during the reperfusion period as a means of preventing myocardial damage. Currently at our institution interventions during this interval are directed toward (1) increasing myocardial oxygen supply by optimizing the myocardial perfusion gradient and perfusate oxygen content, (2) facilitating the intracellular transport of potassium by glucose insulin infusion, and (3) treating any acidosis. These interventions usually result in a sinus rhythm with effective mechanical contraction and minimal difficulties in weaning from cardiopulmonary bypass.

We believe these corrective measures are effective in controlling causative factors that predispose to myocardial damage during cardiopulmonary bypass. The prevention of myocardial injury during cardiopulmonary bypass results in improved postoperative cardiac performance and survival.[12, 13]

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