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Give Me a Shot of Holy Water: Critical Elements in Myocardial Protection during Cardiac Surgery

Curt Tribble, MD, Nicholas Teman, MD

Division of Cardiac Surgery, University of Virginia, Charlottesville, VA, USA

INTRODUCTION

Elective cardiac arrest with a potassium-based solution was introduced clinically in 1956. General acceptance was not immediate, and its use has evolved significantly over the years.
—Erle Austin, 2021

There is a surprising paucity of information on myocardial protection during cardiac surgery in the popular techniques books on cardiac surgery. For instance, Khonsari's otherwise superb book, Cardiac Surgery: Safeguards and Pitfalls in Operative Technique, has only three of its 300 pages that address myocardial protection, while Cooley's book, Techniques in Cardiac Surgery, has none at all. Similarly, the major textbooks of cardiothoracic surgery (Kirklin & Barrett-Boyes, Sabiston & Spencer, and Cohn & Edmunds) all tend to dwell on basic science and pharmacology, while barely addressing the actual techniques and strategies of myocardial protection during cardiac surgical operations. [Khonsari, Cooley, Kouchoukos, Selke, Cohn]

Therefore, there are many aspects of myocardial protection that need to be outlined in a basic introduction to the strategies of providing this protection during cardiac surgical operations. This brief review will not dwell on the makeup of specific solutions that are used for cardioplegia, as it appears from the current literature that there do not appear to be many, if any, clinical advantages of one composition over another. [Comentale 2018, Harbertheur 2014, Russell 2022] Also, we will not address the issues of optimal preservation during heart procurement for transplantation, and neither will we attempt to review the historical literature on various formulations of cardiac protective solutions, a popular subject in the cardiac surgical literature in many earlier decades. [Hearse 1978, Follette 1978, Wechsler 1990, Mentzer 1999]

However, we will address many other issues that need to be considered in protecting the heart during cardiac surgery, including:

a) preoperative considerations
b) cardiopulmonary bypass management
c) avoiding physical injury to the heart
d) avoiding ischemic injury to the heart
e) additional cardiac protective strategies
f) optimizing monitoring during cardiac operations
g) managing reperfusion at the end of the cross clamp time

In many surgical or interventional disciplines, there is a particular procedure that is, or can be, viewed as 'the basic procedure' in that discipline, around which many other procedures in the discipline can be learned or taught. In the realm of cardiac surgery, that procedure is clearly coronary artery bypass grafting (CABG). While this procedure might not have come to be viewed in that light if it were a rarely performed procedure, it is, in fact, not only one of the most commonly performed operation in our discipline, it is actually one of the most commonly performed operations in the United States. On a related note, for most cardiothoracic surgical trainees, a CABG is likely to be the first cardiac surgical operation that each will do in their training. Therefore, most other cardiac surgical cases can be viewed as being 'built around' the foundational strategies and skills learned from participating in and, eventually, performing these operations. Therefore, we will describe the cardiac protection strategies that are, or can be, utilized when performing CABG operations. While we will focus primarily on this clinical situation, the strategies we will cover can be extrapolated to most other cardiac surgical operations. [Yount, 2017]

The patient's outcome correlates directly with the surgeon's attention to a myriad of minor details. This obsession with doing a lot of little things right is the foundation for good surgical results.
—Hiram Polk, MD

You should learn to think about myocardial protection at each stage of the cardiac surgical operations you are performing. We will emphasize thinking about what you want to have happen at each stage, what you need to tell the people on your team to do at certain points in the operation, what you want to look for to ensure that what you want to have happen is actually happening, and what you should feel for, at various points in the operation, with your hand on the heart. Finally, there are some additional considerations more specific to protection of the right ventricle that will be covered in a separate treatise. Let's get started …..

PREOPERATIVE CONSIDERATIONS FOR OPTIMIZING CARDIAC PROTECTION DURING CARDIAC SURGERY

Devising a good plan for cardiac protection starts with pre-operative preparation. For instance, the longer one can

Correspondence: Curt Tribble, MD, Professor of Cardiothoracic Surgery, University of Virginia Health System, Division of Cardiac Surgery, Box 800679, Charlottesville, VA 22908; 434-243-9250 (e-mail: ctribble@virginia.edu).

wait to do a coronary bypass after a myocardial infarction, the better the outcome will be, though decisions about timing of CABG after myocardial infarction are complex and somewhat controversial. [Lee, 2003]

It is helpful to consider the zones of the heart that will be the most challenging to protect during a given operation. Thus, one must, of course, know the individual patient's coronary anatomy. Besides knowing the location and degree of any coronary blockages that may be present, one must also know the anatomy of the coronaries if a valve operation will be done at the same time. For instance, a very short left main coronary artery (LMCA) makes cardiac protection during an aortic valve replacement more difficult, as does a non-dominant right coronary artery (RCA). A short LMCA can make uniform delivery of cardioplegia into the left system more challenging. A non-dominant RCA is often hard to cannulate with a handheld cannula.

One should, of course, know the status of the valves, even on non-valve oriented cases, especially whether or not there is some degree of aortic valve insufficiency, as this condition can make effective delivery of cardioplegia into the aortic root challenging. One must also understand the degree of left ventricular impairment or hypertrophy, as impaired or hypertrophied ventricles need even more careful planning than may be required for patients with more normal ventricles. Aortic calcification found on preop studies can also require additional planning for delivery of cardioplegia (as well as for other technical issues), as you may not be able to clamp the ascending aorta safely or completely. [LaPar, 2013]

There are situations when one might consider placing an intra-aortic balloon pump (IABP) preoperatively, such as severe aortic stenosis, a tight left main coronary artery stenosis, a ruptured papillary muscle, an infarct ventricular septal defect, or unstable angina to aid in ensuring hemodynamic stability during the induction of anesthesia and in the initial stages of the planned procedure. Use of a preoperatively placed IABP used to be quite common, though this strategy is less commonly used in current times. [Ali, 2021]

It is also worth considering managing the heart rate preoperatively, when feasible, in certain situations. For instance, bradycardia should be avoided, or treated, in severe aortic insufficiency to avoid left ventricular distention, which can impair subendocardial perfusion. There are many other issues to consider, in preparing a patient for a cardiac operation, most of which are beyond the scope of this treatise.

MANAGEMENT OF CARDIOPULMONARY BYPASS (CPB) TO OPTIMIZE CARDIAC PROTECTION

Systemic Temperature

You will need to decide what systemic temperature you will cool to. The warmer you run the temperature on bypass the more the heart will warm during the case. This issue is relevant for several reasons including:

a) The warm systemic blood runs from the aortic cannula placed in the ascending aorta through the descending aorta, which is, of course, right behind the heart
b) The potential for collateral coronary flow, especially when coronary artery disease is present, to warm the heart during the time of aortic cross clamping
c) And, the bronchial arterial blood flow to the lungs, which will return to the left atrium via the pulmonary veins and which can continue on into the left ventricle, warming the heart

The heat exchanger temperature should not exceed, at any point:

a) 40 to 42 degrees (It's bad for the brain.)
b) A 10 degree gradient between venous and arterial blood (as nitrogen bubbles may form, which can cause a version of 'the bends,' a condition familiar to SCUBA divers)

These issues are primarily an issue during rewarming, which may be a reason to avoid cooling more than is necessary for a particular clinical situation. Some of these considerations can also be an issue during initial cooling, when cold blood encounters warm tissue (which can cause bubbles to form in local vascular beds.)

Finally, it is worth remembering an old adage about systemic cooling during heart operations, which is: If in doubt or if the situation seems more 'dicey' than you expected, cool more.

Systemic Pressure

You will also need to consider the systemic pressure that will be used during CPB. The lower the pressure, the less the collateral coronary and bronchial blood flow will be. However, you will need to keep the pressure high enough to perfuse the brain and the kidneys and to perfuse past arterial stenoses that may be present elsewhere in the body, to provide adequate blood flow to other important areas of the body. Some practitioners make a cogent argument for aiming to have the systemic pressure on bypass approximate the individual patient's normal mean arterial pressure. [Kanji, 2010 & Futler, 2017] Others have, similarly, made the case for targeting a specific cardiac index or a certain level of oxygen delivery (DO2). [Mukaida, 2019]

A specific point in the operation to be paying close attention to the systemic pressure is when cardiopulmonary bypass (CPB) is started, as, for a variety of reasons, the systemic pressure may drop to quite low levels, at least as CPB is initiated. This particular issue can be ameliorated, at least partly, by keeping the heart relatively full and ejecting during a gradual initiation of bypass. After all, there is rarely a compelling reason to 'crash on bypass.'

In summary, you should define, with your perfusionists and the rest of your team, your plan for the following issues:

a) the systemic temperature (and management of it at various stages of the operation)
b) the systemic pressure
c) the rapidity of onset of bypass
d) the 'rhythm' of the operation, such as redosing of the cardioplegia (for instance: will you redose by time or by giving more cardioplegia between grafts in a CABG?)
e) when systemic rewarming should commence
f) when the cardioplegia or reperfusate should be warmed in preparation for a final 'hot shot' if you plan to use this strategy

PROTECTING THE HEART PRIOR TO AND DURING THE CROSS CLAMP PERIOD

Frigid and paralyzed, the heart does not resist our advances. We do what we must and try to finish quickly, for we know this can be but a brief interlude. With each passing minute we test the limits of the heart's endurance, its capacity for forgiveness.

—Dan Waters, 1998

Avoiding physical injury to the heart during the operation

One aspect of avoiding physical injury to the heart is addressed by looking at the available preoperative studies, such as a chest X-ray or a CT scan, especially in a reoperation. If the right ventricle is plastered against the sternum, injury to the RV is considerable during re-entry.

Also, when dissecting out the heart in a reoperative situation, one has to be quite careful to avoid injury to the epicardial vessels and to old grafts, if present. A longer discussion of other ways to avoid cardiac injury during reoperative cardiac surgery is the subject of a different pair of monographs. [Tribble, 2018 a & b]

A variety of plans can be made to lessen the chance of physical injury to the ventricles from other causes. Obviously one thing to try to avoid is injury to the heart with one's hands (or the hands of your assistants). A finger or thumb in the RV is a terrible sight to behold!

Avoiding Ischemic Injury to the Myocardium: General Considerations

A brief review of the history of the development of cardiac protective strategies starts at least as far back as the late 1890's, when Pratt showed that a heart could be maintained in a beating state using only retrograde perfusion. [Pratt, 1898] In the 1950's, Beck showed that adequate perfusion of heart could be achieved with arterialization of the coronary sinus in setting of complete occlusion of coronary arteries. [Beck, 1935] And, in the 1960's, 1970's, and the 1980's, some of most well-known cardiac surgeons of that era made significant contributions in the development of cardioplegia, including Lillehei, Gott, Shumway, Ebert, Gay, Hammon, Wechsler, & Gardner. [Allen, 1957 / Bixler, 1978 / Hurley, 1964 / Gay, 1973 / Hammon, 2010 / Wechsler, 1990 / Finney, 1990] In the decade that followed (the 1990's), Buckberg and his colleagues continued to add substantially to the science and logistics of the use of cardioplegia. [Buckberg, 1995]

And, it can be said that 'what's old is new again,' as the cardioplegia formulation that Pedro del Nido developed for pediatric heart surgery when he was a resident at The University of Illinois has gained renewed interest in recent years, particularly by surgeons using minimally invasive approaches to adult cardiac surgical operations. [del Nido, 1985]

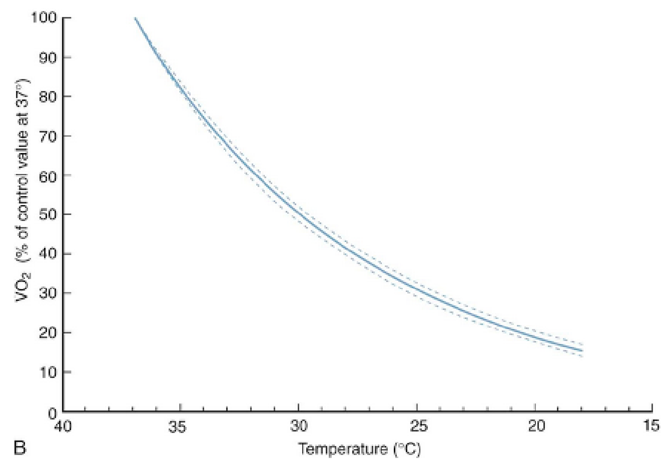
Cardioplegia

Oxygen consumption decreases ~50% for each drop of 10C in myocardial temperature, and the combination of hypothermia and electrical silence can drop myocardial oxygen demand by over 95 %.

The basic purposes of cardioplegia include:

a) cooling the myocardium
b) creating a quiet operative field
c) achieving electrical quiescence
d) delivery of additives in certain situations
e) washout of metabolic byproducts and buffering of acidic metabolites

Cardioplegia is usually infused at 8 to 12^{0}C with a goal of getting the myocardial temperature down to about 15^{0}C. Some surgeons use myocardial temperature probes to monitor adequate cooling of the myocardium, though this practice has become less common in recent years.



A graph demonstrating how oxygen consumption declines with temperature.

Regardless of the technique of infusion of cardioplegia, it is critical to deair the delivery system prior to administering cardioplegia. Deairing starts by letting each of the cannulas backfill once they are inserted. A trick for deairing the coronary sinus catheter after it is inserted is to occlude the sinus with a finger between the ostium of the sinus in the RA and the cannula's tip. One also has to be sure that air is not entrained in an open side arm in the cardioplegia delivery system which could push air into the heart vessels when the cardioplegia is delivered. While some air can be flushed out of the coronaries with retrograde infusion, some small bubbles may remain in the coronary circulation, and this air can affect blood flow in the heart for many hours by physically obstructing coronary flow.

Strategies for delivery of cardioplegia

The two primary strategies for delivery of cardioplegia solutions are the antegrade and retrograde routes (or a combination of the two). We'll review the cannulas used for delivering these solutions later in this treatise, as well as describing some tricks for their use.

Note: You should feel under the proximal aorta to ensure that the aortic cross clamp is all the way across the aorta, prior to giving cardioplegia. If it is not, you will usually feel a thrill on the posterior portion of the aorta as blood passes through the unclamped portion of the aorta. This situation arises more commonly when the aorta is large or calcified or in a reoperative case if the aorta has adhesions around it. If this issue has not been detected early in the cross clamp period, it should be suspected if electrical or mechanical activity appears to have resumed.

One should always be looking for additional ways to deliver cardioplegia or blood to the heart throughout the case, including through coronary bypass grafts, once they are constructed. Furthermore, one should be ready to consider changing strategies based on which parts of the heart are likely to be most ischemic at any specific point in the operation. You should run the cardioplegia through one system at a time, at least on occasion, to ensure that both the antegrade and the retrograde systems are working the way you want.

Finally, in considering the optimal temperature of the cardioplegia to be delivered, it is reasonable to remember that cold is good, so the lower the temperature of the cardioplegia the better, at least until you are near the end of the cross clamp period. It's worth noting that, while the O2 dissociation curve shifts to the left when blood is cold (thus, in theory, delivering less oxygen than when the solution is warm), the solubility of both O2 and CO2 in plasma rises markedly in colder solutions, which, it has been claimed, may overcome at least some of the loss of oxygen delivery caused by the left shift of the O2 dissociation curve. Furthermore, blood is a very good buffer, which is thought by many to be one of the most important benefits of blood cardioplegia.

ANTEGRADE CARDIOPLEGIA

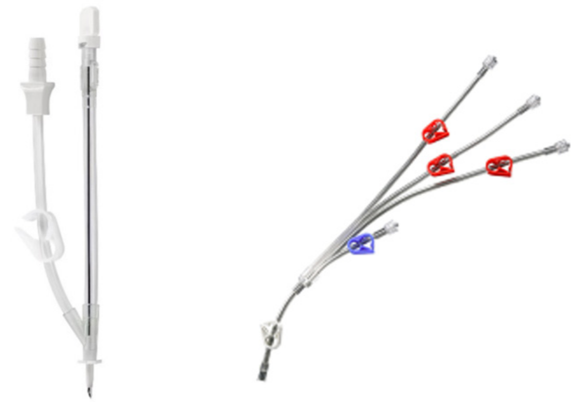
Antegrade cardioplegia is given primarily through the aortic root. This route of delivery does require a competent aortic valve, of course. Antegrade cardioplegia can also be delivered by handheld cannulas, with direct infusion into the left main and right coronary arteries when the aorta is open, especially during aortic valve or aortic root operations.

Devices for antegrade delivery of cardioplegia

The most commonly used device used to deliver cardioplegia into the aortic root is the DLP device, which is usually used with a multi-head adapter, especially in coronary bypass operations.

Avoiding injury when placing the antegrade cardioplegia cannula

When placing the antegrade cannula it is important to avoid hitting the back wall of the aorta. Some tricks for protecting the back wall include pulling up on the pledgetted suture that will be used to secure the DLP cardioplegia cannula once it is placed, so that the anterior aortic wall is pulled away from the back wall. Also, it is best to place this cannula while the aorta is distended (rather than after the clamp is on, when the aorta may be flaccid). One can also make a tiny linear slit in the aorta with an 11 blade to allow the needle to pass into the aorta easily. This maneuver is especially important when the cannula is being placed into a cloth graft, as might be the case



The DLP aortic root cardioplegia cannula and the multihead adapter. (Interestingly, DLP are the initials of the names of the children of the inventor of this device.)

after an ascending aortic replacement. It's also important to place these cannulas in the middle of the most anterior part of the aorta, not only so that the needle won't hit the side of the aorta during insertion, but also because this position is best for evacuating air at the end of a case in which the chambers of the heart have been open.

In aortic valve cases, one should consider not putting a DLP cannula in the aorta early in the case. This cannula may get in the way or cause injury to the aorta when it is moved around while working on the aortic valve. A straightforward technique to consider in this setting is to use an 11 blade to make a small incision in the aorta after the cross clamp is put on. A so called 'double bubble' handheld cardioplegia cannula can then be used to infuse cardioplegia for the initial dose through that small incision. A DLP cannula can then be placed after the aorta is closed back up (for subsequent cardioplegia delivery and deairing). It is worth noting that slits made in the aorta for these reasons should be in line with the axis of the aorta, as a slit make across the axis of the aorta may, rarely, become a lead point of an aortic dissection.

The optimal pressure for delivery of antegrade cardioplegia

An important concept that is not often discussed in the administration of the antegrade cardioplegia is the optimal pressure for that delivery, which should be in a range between normal diastolic and normal mean blood pressure (though this pressure is rarely monitored). [Salerno, 2007] Lower pressures may result in inadequate protection while higher pressures may result in myocardial edema or even, potentially, coronary artery injury. Aspects of the individual patient's situation may be relevant to the pressure that might be optimal, such as LV hypertrophy, pre-existing arterial hypertension, the presence and degree of coronary stenoses, and the viscosity of the cardioplegia solution (blood vs crystalloid). Specifically, the recommended aortic root pressure during the administration of cardioplegia should be between 60 and 80 mmHg for most cases. (This issue may be even more important in protecting donor hearts being procured for transplantation than in protecting the myocardium during routine cardiac surgery.) Again, most surgeons ascertain the infusion pressure of antegrade cardioplegia by feeling the aorta, while very few monitor the infusion pressure directly. There is actually a surprising paucity of information about precisely monitoring the infusion pressure in the literature. [Young, 1996]

Challenges in Delivering Antegrade Cardioplegia

No antegrade delivery strategy will work, of course, if there is aortic insufficiency (AI). If there is AI, retrograde cardioplegia should be started first. [Tribble, 2018] In the setting of mild AI, sometimes a bit of pressure on the aortic root with a finger or sponge stick can create a bit of additional coaptation of the aortic leaflets. The LV can also be held by hand to prevent distention in the setting of mild AI but this strategy is often not optimal unless combined with other routes of delivery of the cardioplegia.

In cases in which the aorta needs to be opened (which is rarely the case in a standard CABG operation, unless AI is found to be present), handheld cannulas should be used to infuse cardioplegia into the two coronary ostia. A variety of cannulas are available for the direct infusion of cardioplegia into the coronary ostia.

A handheld antegrade cardioplegia cannula.

When the aortic root is opened, the first cardioplegia dose is usually delivered into the left main coronary artery. A small pediatric olive tip cannula can be used for smaller right coronary arteries. One should stop the flow of retrograde cardioplegia when handheld cardioplegia is being given so that your perfusionists can tell you how well the cardioplegia is flowing. It is not uncommon to see that these handheld cardioplegia cannulas do not allow optimal flow, leading to a need to manipulate the cannulas to assure proper flow. You need to remember that the coronaries come off the aorta at a bit of an angle, so the LMCA cannula should be directed slightly towards the left shoulder and the RCA cannula should point slightly towards the right hip. Sometimes it can be helpful to bend the cannula a bit to facilitate optimal delivery of the cardioplegia.

It's also important to know how long the left main coronary artery is when infusion of cardioplegia into the coronary ostia will be used. If the left main is short, you have to consider the possibility that you may be infusing cardioplegia into only the left anterior descending coronary or only into the left circumflex coronary, which would result in adequate protection of only one of those territories.

One must be aware that some coronary perfusion cannulas can injure the coronary ostia. For instance, there is a cone shaped coronary perfusion cannula that may be rough enough to injure the coronary ostia occasionally.

Also, one needs to keep in mind the challenge posed by a non-dominant RCA. Often the ostium of a non-dominant RCA is too small even for the smallest olive tipped pediatric coronary cannula. This anatomy adds to the need to have a well thought out plan for protecting the RV (which might include dual venous cannulation, alternate retrograde cardioplegia strategies, cooler systemic temps, getting more cardioplegia in before opening the aorta if possible, more topical cooling of the RV, such as wrapping ice in a lap pad and leaving it on the surface of the heart, opening the right atrium to place a purse string around the coronary sinus orifice, or placing a suture around the coronary sinus from the inferior wall of the heart, to increase the scope of delivery of the retrograde cardioplegia, as noted below.

RETROGRADE CARDIOPLEGIA

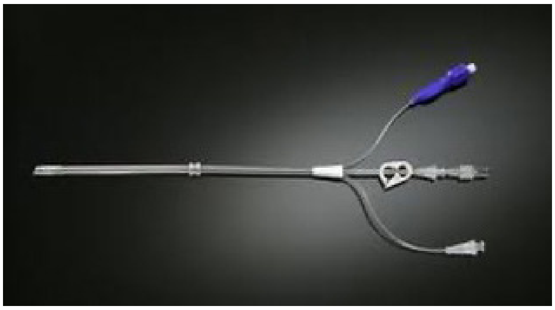
Advantages of using retrograde cardioplegia (or adding it to antegrade cardioplegia) include the facts that:

- Air can be flushed out of the coronary arteries
- Cardioplegia delivered in a retrograde fashion will likely be helpful in the setting of significant obstructions of the coronary arteries
- One can decrease the amount of coronary ostial instrumentation required in operations on the aortic valve
- And, the use of retrograde cardioplegia lessens the need to remove retractors during mitral valve surgery (as the retraction used in mitral valve surgery usually makes the aortic valve insufficient, which makes the administration of antegrade cardioplegia more challenging).

Techniques for the delivery of retrograde cardioplegia were developed after the antegrade techniques were developed (though there were some early forays into this approach as noted above). We have covered the techniques for delivering retrograde cardioplegia in greater detail in a separate treatise. [Tribble, 2018]

Retrograde cardioplegia delivery devices and tricks for their insertion:

Retrograde catheters can be placed blindly (by feel) through the right atrium in most cases. If direct insertion is required, the right atrium can be opened (if the cavae are cannulated and taped) and the cannula can be inserted directly into the sinus, usually with a purse string around the ostium of the sinus. This stitch, if used, needs to be placed as close to the edge of the orifice as possible to avoid injury to the conduction system. It can be held in place with a Rummel tourniquet. If this strategy is used, you can pull the retrograde catheter back to the level of that stitch, with the balloon inflated, which will obviously allow delivery of the cardioplegia to more of the coronary veins than if the retrograde cannula is left 'deep' in the coronary sinus. Retrograde cannulas, especially smaller ones such as the pediatric retrograde cannulas, can also be placed directly into a reasonable sized coronary sinus, through a purse string placed in the inferior wall of the proximal coronary sinus, outside the heart by exposing the inferior wall of the heart.



A retrograde cardioplegia cannula.

There are some good tricks for getting the retrograde cannula optimally inserted into the coronary sinus. One trick is that it's easier to put these cannulas in from the left side of the table. The purse string for the cannula should usually be placed inferior to the venous cannula. It is worth trying to keep the tip of the cannula 'hugging' the atrial wall as you pass it from its insertion site towards where you think the coronary sinus orifice will be.

Another trick is to realize that some advantage can be gained by spinning (ie, twisting) the cannula to keep the beveled tip from catching on the side walls of the coronary sinus or its branches. You can sometimes get some help from your anesthesiology colleagues and the transesophageal echo. Finally, you should strive to get the cannula as far as it will go into the coronary sinus.

And, here's a 'science project' to consider: put your finger on the surface of the inferior wall of the heart at the junction of the coronary sinus and the right atrium when giving retrograde during an AVR. You will almost always see more 'black blood' come out of the right coronary artery (RCA) when you do this, which will demonstrate that more blood is now being given retrograde into the area supplied by the RCA.

Thus, a useful technique to enhance the delivery of retrograde cardioplegia is to encircle a the coronary sinus with a 2-0 or 3-0 Prolene, on a large needle, placed around the coronary sinus near the junction of the coronary sinus with the right atrium, so that the cardioplegia cannula, with the balloon inflated, can be pulled back against this encircling stitch, which will not only keep the cannula in place during the planned operation but will also perfuse more of the veins draining into the sinus near its junction with the right atrium. It is important to note that it is safe to deliver both antegrade and retrograde cardioplegia simultaneously. There is adequate drainage via the Thebesian veins to allow this strategy to be used without concern. [Tribble, 2018]

While retrograde cardioplegia is almost always delivered through the coronary sinus, it is possible to give it directly into the right atrium (this strategy does, however, have some specific challenges), as only 50 to 60% of the venous drainage of the heart flows into the coronary sinus, while the rest of the drainage is through the Thebesian Veins draining directly into the right atrium. This anatomy has led some surgeons to infuse cardioplegia directly into the right atrium (aided, of course, by the use of caval tapes, as well as by occlusion of the pulmonary artery). This technique was used consistently by Alain Carpentier in his mitral valve repairs. [Carpentier, 2010]

One specific note about the use of retrograde cardioplegia in CABG cases is that the right coronary system should be grafted first, if indicated, as the retrograde cardioplegia does get to the part of the heart supplied by the left coronary system better than it gets to that supplied by the right coronary system. As noted earlier, one should always use a multihead or 'octopus' tubing for the cardioplegia setup, so that the cardioplegia can be delivered in as many different ways as feasible (aortic root, coronary sinus, individual coronary grafts, and coronary ostia). Many surgeons like to put the blue head of this multihead adapter on the coronary sinus catheter and use the red heads for the root, vein grafts, or hand held coronary cannulas.

Monitoring the pressure in the coronary sinus

Another important point is that the pressure in the sinus must be monitored when the cardioplegia is being infused. This pressure must be monitored to ensure that the cannula is in the right place, that the balloon is blown up, that the cannula has not fallen out during the operation, and that there is no persistent left superior vena cava (SVC). (Hint: A persistent left SVC should be suspected if the innominate vein is diminutive or absent.) The absolute pressure is not all that important. What is important is to see a rise in the coronary sinus pressure each time the infusion is running. Usually, the coronary sinus pressure is displayed on the monitor in place of the pulmonary artery pressure, since the measurement of the pulmonary artery pressure is unnecessary while on bypass.

The checklist to run through when delivering retrograde cardioplegia includes:

a) checking to see that pressure displayed on the monitor has risen
b) asking the perfusionist if the cardioplegia is running well
c) checking the veins of the heart for distention and to see that they are changing color from blue to red
d) seeing that dark blood is running out of the coronary ostia when aortic root is open

A final note about the use of retrograde cardioplegia is that it may have an important role in reoperative CABG surgery with 'live' grafts, with the thought that this strategy may reduce the risk of embolization of clot or atherosclerotic debris in old vein grafts, which can occur with antegrade cardioplegia, especially after manipulation of diseased grafts has occurred. (See the separate treatise on reoperative cardiac surgery for a more extensive discussion of how to manage 'live' but diseased vein grafts during reoperations.) [Tribble, 2018]

INITIATING CARDIAC ARREST

Once the infusion of antegrade cardioplegia is started, one should have a checklist (at least a mental checklist) to be sure it is proceeding properly. Processes such as these obviously require efficient and effective communication with your teams. [Marvil, 2017]

a) check for appropriate distention of the aorta
b) with your right hand under the heart, ensure that the LV is not distending
c) feel also for proper positioning of the retrograde catheter
d) ensure that the heart is arresting

If the aorta isn't distending or if the heart isn't arresting expeditiously:

a) start at the pump and work towards the heart, considering the following:
   i. pump malfunction
   ii. kinks in the delivery line
   iii. a clamp on the line that may be closed
   iv. another 'head' of the multihead adapter is open (with blood flowing into some 'hidden spot' under the drapes)
b) start at the aorta and consider the following:
   i- the cross clamp isn't all the way across the aorta (feel for a thrill in the back of the aorta, which will indicate that systemic blood is flowing into the root, a circumstance more common that one might think)
   ii- unrecognized aortic insufficiency (as evidenced by LV distention with infusion of cardioplegia into the aortic root)
   iii- coronary disease not allowing adequate and uniform antegrade cardioplegia delivery

Planning the timing and routes for delivery of cardioplegia

One should make a plan with the OR team plan for the timing and the dosing of the cardioplegia. While it is likely that most surgeons give more cardioplegia than is necessary, there are some surgeons who go for extended periods of time without reinfusing cardioplegia. However when it is relatively convenient to deliver and does not slow down the operation, it seems as though more cardioplegia would likely be better. Some principles of timing include infusing more cardioplegia and infusing it more often when the myocardial temp rises or ventricular fibrillation is seen. Most surgeons give doses of cardioplegia about every 20 minutes in valve cases or between each graft in a coronary bypass case. And, most surgeons give about 500 cc's of cardioplegia with each of the repeated doses.

To be more specific about cardioplegia delivery in CABG cases, antegrade cardioplegia is usually started first via the aortic root cannula, while ensuring adequate distention of the root. Then, the retrograde cardioplegia is started and is run simultaneously. (We call that strategy the 'AC/DC approach.') One must ensure that the pressure in the coronary sinus rises appropriately with each infusion, as noted earlier. Then, the usual order of creating the grafts is: RCA, followed by all non-LAD grafts, with the IMA to LAD being done last (for technical reasons, not for priority of myocardial protection). Cardioplegia is delivered down the coronary bypass grafts after the construction of each graft. Once the internal mammary artery (IMA) graft to the LAD graft is done, one can remove the bulldog clamp on the IMA and allow warm blood to run through the IMA, as well as through the retrograde catheter, and all vein grafts, while the proximals are being constructed. The heart will virtually always start beating on its own when this approach is used and defibrillation will only rarely be required. After all, spontaneous defibrillation of the heart cannot be a bad thing! [Tribble, 2022]

One caveat may be worth repeating, which is that many surgeons will avoid giving antegrade cardioplegia first in a reoperative case if there are patent but diseased vein grafts, because of concerns that debris in those grafts might embolize, especially after being manipulated during the initial dissection required in a reoperation. [Tribble, 2018]

CARDIOPLEGIA SOLUTIONS

There are many cardioplegia solutions available. [Lopez-Mendez 2017, Eris 2022, Veres 2015, Commentale 2018, Russell 2021] Most surgeons use some type of blood cardioplegia, which is actually blood diluted with cardioplegia (usually in a 4 parts blood to 1 part crystalloid ratio). This strategy of cardioplegia delivery has been called 'mini plegia.' [Gong, 2015] The system is usually set up to deliver ~8 meq per liter of magnesium and 30 meq of potassium in the initial dose and 8 meq per liter of magnesium and 6 meq of potassium in subsequent doses. Usually one liter of cardioplegia is delivered antegrade in the first antegrade dose, followed by 500 milliliters via the retrograde cannula, if retrograde delivery of cardioplegia is being used. The temperature of these solutions is generally about 10 degrees centigrade.

However, there has been a recent revival of interest in crystalloid solutions such as the del Nido solution or Celsior, which may provide some advantages. However, crystalloid (or solutions mixed with only a small amount of blood) can make finding coronaries difficult in a CABG operation. A thorough discussion of the history and current status of all the cardioplegia solutions that have been or are being used is beyond the scope of this review. As noted earlier, the currently available literature suggests that no one formulation is significantly better than another.

A once popular set of additives for blood cardioplegia was developed by Dr. Gerald Buckberg and his associates. The primary additives were glutamate and aspartate, which are Krebs cycle intermediates, as most will remember from their biochemistry classes. These additives were well supported by extensive laboratory research, but it has been challenging to prove their value conclusively in clinical use. Currently these additives are used most often for warm induction or for a hot shot delivered toward the end of the cross-clamp time. [Follette, 1978]

In summary, it is probably fair to say that the more (cold) blood cardioplegia that is delivered during cross-clamp period, the better. Blood not only delivers oxygen but it also is an excellent buffer. And, it is worth noting that infusing warm blood that is not mixed with cardioplegia, even with the cross-clamp on near the end of the clamp time, is close to being the equivalent of having the cross-clamp off. [Tribble, 2022]

ADDITIONAL CONSIDERATIONS FOR PROTECTION OF THE HEART DURING CARDIAC OPERATIONS

Avoid getting air into the coronaries:

You must deair all cardioplegia lines early (and often) as already mentioned. You can consider flooding the field with carbon dioxide to displace air from the chambers of the heart, since CO_2 is very soluble in blood, while the nitrogen in air is not. One can aspirate or vent air from the chambers of the heart once the heart is closed up.

A particular situation when air can get into the coronaries during an operation is during mitral valve surgery, when air can get into the root from the LV between infusions of cardioplegia, especially when using squirts of saline into the ventricle to test the valve. You can minimize this issue by venting the root carefully prior to delivering each subsequent dose of cardioplegia.

Avoid allowing particulate material to get into the coronaries:

This issue is of greatest concern when debriding a calcified, stenotic aortic valve. Some surgeons place a 'greasy' gauze pad in the LV to catch particles during debridement (both the Mayo Clinic & the Brigham surgeons describe using this technique), and some put the end of an umbilical tape in the orifice of the left main coronary artery (described by the Mayo surgeons, though possibly less important when retrograde CP is used). If a gauze pad is inserted into the LV during the debridement of a calcified aortic valve, you should attach a heavy suture to it, both for ease of retrieval and to ensure that it is, indeed, removed after the debridement of the valve is completed.

Venting to protect the heart:

Besides evacuating air that might get into the coronaries, left ventricular vents are also used to:

a) avoid distention of the left ventricle
b) enhance visibility during cardiac operations
c) evacuate warm blood from the heart (which can get to the heart via venous return to the right atrium, bronchial artery blood returning to the left atrium, and from coronary collaterals)

Paying close attention to the venting of the heart is particularly important when the cross clamp is off and the heart is not beating, as even a trace of aortic insufficiency can distend the heart more quickly than one might expect.

It is worth noting that if an LV vent is 'pulling too hard,' mild aortic insufficiency may be exacerbated, which is a consideration when giving cardioplegia into the root. That is, one may need to cut back on the vent suction while giving cardioplegia under these circumstances. Also, if mild LV distention seems to be occurring after arrest occurs with antegrade cardioplegia, one can sometimes apply pressure to the left side of the aorta by pressing on the RV outflow tract which may allow some additional coaptation of the aortic leaflets.

Topical cold strategies to aid in protecting the heart:

Arresting the heart and keeping it cold constitute the major components of myocardial protection. However, in clinical practice it is virtually impossible to keep the heart appropriately hypothermic: it tends to rewarm from the extracardiac environment, as a consequence of inadequate regional cooling and …. because of collateral circulation.

—Andrew Wechsler, 1990

It's worth remembering that Doctors Norman Shumway and Richard Lower developed their early cardiac protection strategies at Stanford using primarily topical cold saline and ice. However, this protection strategy can come at a price, as the phrenic nerves, particularly the left phrenic, are vulnerable to cold injury and can be impaired by this injury. This vulnerability of the phrenic nerves has led to attempts to insulate them from the cold. Wraps and cooling jackets that surround the heart have been developed to aid in cooling the heart during cardiac surgery. Ice can be wrapped in a lap pad and placed on top of the heart. Ice can also be placed inside the heart. Dr. Alain Carpentier colorfully called the ice cubes that he liked to insert into the heart during mitral valve operations, "heart suppositories". [Carpentier, 2010] Finally, once the initial induction of arrest has occurred, one should consider forgoing the use of large amounts of additional topical cold saline or ice to lessen the risk of injuring the phrenic nerves.

Other strategies for keeping the heart cold:

Bi-caval cannulation, with tapes encircling the vena cavae, will keep the warm venous blood away from the right atrium, the right ventricle, and the ventricular septum. Applying vacuum to the venous reservoir can also aid in keeping warm blood away from the heart, even in the absence of caval tapes. One way or the other, in every cardiac case, one wants the right atrium to be well drained. Vents placed in the pulmonary artery, the left atrium, or the left ventricle can also help divert the warm blood that returns to the heart from the lungs as a result of bronchial arterial blood flow.

As noted earlier, one must remember that the warm blood being infused into the ascending aorta through the aortic cannula (the systemic return from the pump) runs immediately behind the heart in the descending aorta. Thus, placing a cold pad behind the heart in the area of the descending thoracic aorta can provide some separation of the cold heart from the warm aorta, though, again, one must be careful to avoid making the left phrenic nerve too cold.

Some surgeons have touted the use of atrial cooling as well, as there is some data that this will decrease the incidence of post-operative atrial fibrillation. Atrial cooling can be achieved by:

a) caval tapes (since caval tapes, obviously, keep warm blood away from the right atrium)
b) infusion of cold solutions into the atrium
c) topical cooling with cold pads or even a drip of cold saline onto the atrium

In summary, the strategies used to minimize rewarming of the ventricles include:

a) decreasing systemic temp
b) decreasing CPB flow (and pressure, if collaterals are present)
c) adding vacuum to enhance venous drainage
d) using bi-caval cannulation
e) venting the LV and / or the PA
f) cooling the surface or the interior of the LV with cold solutions
g) putting ice inside the heart

MONITORING THROUGHOUT THE OPERATION TO ENSURE OPTIMAL CARDIAC PROTECTION

The systemic blood pressure must be monitored accurately. The desirable blood pressure during the period of aortic cross-clamping requires a balance between perfusing the rest of the body and controlling any collateral blood flow to the heart that may be present.

The same sort of thinking is required in monitoring and managing the temperature of the systemic blood. That is, colder systemic perfusion temperatures are better for the heart, while more moderate hypothermia may be better for the rest of the body.

Some surgeons monitor the temperature of the heart with temperature probes. They use this information to decide how and where to deliver cardioplegia and at what intervals it should be delivered. For instance, if the heart is rewarming rapidly, the systemic temperature can be dropped, cardioplegia can be given more frequently, or better venous drainage (with vacuum or caval tapes) could be utilized.

The electrical state of the heart should, of course, be monitored. The primary focus of monitoring the EKG on the monitor during the cross clamp period will be to watch for the return of electrical activity, which will usually precede the return of mechanical activity. If electrical activity is noted, either on a monitor of by direct observation, a decision can be made about whether earlier redosing the cardioplegia or, perhaps, additional venting or topical cooling is warranted.

As noted above, the pressure in the coronary sinus must be monitored when retrograde cardioplegia is being infused. The exact pressure is not as important as is being able to see that the pressure rises when the infusion is occurring. If the pressure does not rise, the retrograde cannula may have come out of the coronary sinus, a not uncommon occurrence.

A pulmonary artery (PA) catheter can be used to optimize the management and performance of the right ventricle at the completion of the case, and a PA catheter is particularly useful in patients with sick hearts or during implantation of LVAD's.

A femoral line or some other very reliable arterial line can be valuable, especially in long cases in patients with sick hearts, to ensure that systemic blood pressure is being monitored accurately. These lines, of course, can also be used to provide expeditious access to the femoral artery for an alternative cannulation site or for the expeditious insertion of an intra-aortic balloon pump. Some surgeons say that they think of a femoral line as having a 'talismanic effect' when placed prior to going on pump in complex cases, perhaps 'warding off' undesirable outcomes.

'THE HEART SPA' – MANAGING THE EARLY PERIOD OF REPERFUSION

Some strategies for reperfusing the heart prior to cross clamp removal

As noted earlier, a very effective way to reperfuse the heart near the end of the cross clamp time is to provide as much warm blood to the heart as is feasible, using the retrograde cannula and the coronary grafts (including the IMA). This strategy can be employed while sewing the proximal anastomoses in a CABG operation (though one has to be careful of blood being ejected from the proximal sites if the heart starts beating). An empty beating heart, even when warm, requires only about 10% of the oxygen of a working heart. [Tribble, 2022]

Avoiding ventricular distention around the time of the cross clamp removal

A left ventricular vent can be of help when the threat of distention is a consideration, as in the setting of mild aortic insufficiency. The aortic cross-clamp can be used to minimize (or relieve) distention as well. Having the heart beating will also help minimize distention. Therefore, prior to removing the cross-clamp, it can be advantageous to have the heart beating. It's worth noting that repeated defibrillations can injure the myocardium. It's also worth considering placing the left ventricular pacing wires before taking the cross clamp off, as it is often easier to put them on at that point, and it can be useful to pace with those wires to keep the heart beating, at least slowly, during the initial period after removing the cross clamp. You can also consider placing the posterior chest tube in at this point, as well, both to lessen the chance of pulling out the ventricular pacing wires, as the operation winds down, and to position the posterior tube optimally. Remember that all modern mechanical aortic valves have an obligatory amount of aortic insufficiency, which is designed to allow the hinges to be rinsed with each beat, and this fact means that one needs to be even more cognizant of the possibility of ventricular distention after the replacement of the aortic valve with a mechanical valve, at least until the heart is beating appropriately.

Managing the coronary perfusion pressure when preparing to come off cardiopulmonary bypass:

Since the coronaries are perfused primarily during diastole and since the pressure gradient across the coronary capillary bed is determined by subtracting the right atrial pressure from the systemic diastolic pressure, the coronary perfusion pressure can be calculated. If this coronary perfusion pressure falls below ~25mm Hg the heart may be inadequately perfused. Under these conditions, an intra-aortic balloon pump can be considered, as when the balloon of this device inflates during diastole, the diastolic pressure will be much higher and, thus, the coronary perfusion pressure will be concomitantly improved. Obviously, one can always continue, or resume, cardiopulmonary bypass until stabilization of heart rhythm and function is optimized. On a similar note, it is worth noting that having an optimally dilated IMA enhances early perfusion of the newly revascularized myocardium. Optimizing IMA dilatation is covered in a separate write-up. [Tribble, 2017]

QUESTIONS TO ASK YOURSELF ABOUT CARDIAC PROTECTION AT EACH STAGE OF THE CASE:

- What do you want to have happen at each stage?
- What do you need to tell the other people in the room to do? (systemic pressure at various points, rate of cardioplegia flow, shifting to warm blood, etc)
- What observations do you need to make? (aortic distention, LV distention, position of retrograde catheter, color of blood coming from coronary ostia, distention and color of coronary veins, especially when using retrograde cardioplegia, etc, etc, etc…..)

EARLY POSTOPERATIVE MANAGEMENT:

There are many points to be made regarding early postop management after a cardiac surgical operation, and most of these points will be covered elsewhere. However, it is important to avoid having the heart struggle during separation from cardiopulmonary bypass. Remember the old adage that 'the best ventricular assist device is another 30 minutes of cardiopulmonary bypass' allowing the heart to rest and recover. Management of the right ventricle during this time is also critical. The management of the right ventricle will also be covered in a separate treatise.

CLOSING COMMENTS: STANDARDIZATION, SIMPLICITY, AND SPEED

Simplicity is the ultimate sophistication.
—Leonardo da Vinci

We agree with Dr. Eric Roselli who, in a recent letter to the editor of the Annals of Thoracic Surgery, commented on the need to simplify cardioplegia strategies when feasible. He invoked 'The KISS Principle' (ie, Keep It Simple, Stupid). He noted that the most important principles for delivering safe myocardial protection are assuring that the cardioplegia solution is actually being delivered to as much myocardium as possible and that it is done simply and often. [Roselli, 2021]

Fast is good, but accuracy is everything.
—Wyatt Earp

On a related note, our colleague of many decades, Dr. Irv Kron, noted in Mastery of Cardiothoracic Surgery, that "if we questioned 10 experts in cardiac surgery, we would hear 10 different myocardial protection strategies. However, the individual surgeon must have a consistent approach…… No matter what technique is used, time is of the essence, and this must always be considered by the operating surgeon." [Kaiser, 2007]

SUMMARY

You don't decide your future. You decide your habits and your habits decide your future.

Protecting the heart during cardiac surgery is more nuanced than many realize. A good cardiac surgeon must have the habit of using all 'the tricks of the trade' to protect the heart optimally in a wide array of circumstances. Still, it is also worth noting that the simplest plan may sometimes be the best plan. Thus, you should keep in mind that your cardiac protection strategy should be as simple as is practical and effective but not simpler. And, whatever strategies you chose to employ, your results will often depend on your habits, as the more you can standardize your procedures, the more reproducible your results will be.

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