Management of the Pediatric Patient After Cardiac Surgery

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The medical management of the child with congenital cardiac disease prior to and following cardiac surgery has made a substantial contribution to the improved morbidity and mortality attributed to surgical advances. This paper provides a framework for understanding the problems that arise in the perioperative period and a systematic approach, by organ system, to monitoring and management of these problems. The discussion is intended to be of general application, focusing on initial stabilization following surgery and the cardiorespiratory, renal, metabolic, hematologic, and neurologic alterations that result from surgery with cardiopulmonary bypass. An approach for the management of the low output state is also provided. Little attempt has been made to focus on problems unique to a specific type of cardiac disease or certain operative approaches. Rather, it is the contention that an understanding of general principles and an appreciation of the common problems will provide adequate preparation for those responsible for the care of the child.

Although much of the improvement in survival and reduction of morbidity in children with congenital cardiac disease has occurred as a result of advances in surgical techniques, the management of the child prior to and following surgery has also made a substantial contribution to the outlook of these children. It is the aim of this discussion to provide a framework for the management of the pediatric patient undergoing cardiac surgery and for the anticipation and recognition of problems that arise during the post-operative period.

PRE-OPERATIVE CONSIDERATIONS

Much can be done prior to surgery to reduce the risks of the surgical procedure and to help provide a smooth course for recovery. One should certainly be familiar with both the patient and family and have a knowledge of the intended surgery, expected outcome, and potential complications. A considerable amount of information can be obtained from the pre-operative examination of the child and a detailed review of the cardiac catheterization and any other physiologic data available. One should note particularly whether there is evidence of congestive failure, respiratory compromise, or chronic malnourishment. Each of these factors markedly increases the surgical risk and each tends to prolong the course of recovery. It is often desirable to minimize the effect of such factors by adjusting medications and therapies prior to surgery. This may entail, on occasion, starting an infusion of in-
travenous vasoactive medications, initiating mechanical ventilation, or beginning parenteral nutrition. Since each of these have attendant risks, generally such therapies should be instituted in an intensive care unit suited for appropriate monitoring.

Vasoactive medications are indicated when circulatory failure is present or shock is impending. This may be manifest by metabolic acidosis, which is poorly compensated, or by other signs of a very low cardiac output (cf. physical examination). In the newborn or young infant, this state may have been precipitated by closure of a patent ductus arteriosus in the presence of left heart obstruction, thereby restricting systemic blood flow [1]. In such a setting, a prostaglandin infusion (PGE$_2$), which may augment pulmonary blood flow by opening the ductus arteriosus, may be beneficial in addition to the use of fluid therapy and inotropic medications aimed at improving cardiac output [2,3]. In this setting, PO$_2$ and pH may rise substantially, allowing the infant to stabilize prior to surgery. In the older child, fluid loss, infection, or anemia may cause sudden decompensation, and these conditions should be treated while supporting the circulation with inotropic drugs as will be outlined later.

Mechanical ventilation may also be necessary in some patients with severe circulatory compromise causing acidosis, hypoxemia, or both. When the work of breathing is large and the circulation unstable, supportive ventilation may avoid a respiratory arrest during transport or during surgical preparation. Much of the risk of intubation can be reduced by prior preparation; this includes necessary equipment, proper suctioning apparatus, appropriate assistance, and time for the child to breathe oxygen prior to intubation.

Finally, there are some children who are cachectic as a consequence of their chronic circulatory failure and its treatment. Most commonly, these are patients with low systemic blood flow and pulmonary edema, such as occurs with a large volume left-to-right shunt. Supplementation of their enteral nutrition when possible or beginning parenteral nutrition may serve to improve the post-operative recovery. This is particularly important if there are poorly healed skin wounds pre-operatively or if there is a likelihood of prolonged support post-operatively.

**TRANSPORT AND INITIAL STABILIZATION**

When a child is transported to or from the intensive care unit or other perioperative care facility, intravascular catheters, a Foley catheter, chest tubes, an endotracheal tube, and other such devices are often in place. This is a time of particularly high risk since the child may not yet be stable and numerous opportunities are available for monitoring equipment and lines to become disconnected. Because of this it is essential never to transport a thrashing patient. It is worth the time and effort to stop, ensure that all lines are properly fixed, and attend to the causes of the patient’s agitation before proceeding. One should be certain that sufficient oxygen is being provided and the child is breathing or being ventilated adequately. At this point it may be necessary to provide sedation and possibly muscle relaxation to transport the patient safely. It is easy for the child to be buried beneath the equipment; therefore, it is helpful to have him partially undraped so that at least the chest and face can be well observed and all intravascular catheters are visible.

Upon arrival at the intensive care unit, there needs to be an organized approach to the patient so that the most critical needs are tended to first, while, in the end, nothing of importance is overlooked. Since it is easy for chaos to ensue until transfer
of care is completed, it is essential initially to ensure that the most vital of functions—respiration and circulation—are grossly intact. To establish that ventilation is adequate, one must be certain that the patient is breathing, or being breathed reliably, and that gas exchange is adequate. The movement of the chest with it undraped should be observed, and both sides of the chest (preferably in the axillary area) should be listened to. One should inspect the endotracheal tube and ensure that it is well secured and, following this, an arterial blood gas measurement should be made. The adequacy of circulation should be quickly ascertained by checking heart rate, palpating both central and peripheral pulses, and checking peripheral perfusion.

Once it is determined that the patient is stable, it may then take approximately fifteen minutes for the nursing staff to organize the lines and equipment for monitoring, check fluid levels, secure the patient, and make him comfortable. To institute transfer of care it is helpful to have at least two nurses, a respiratory therapist, and the physician who will take responsibility for the patient’s care. One nurse may attend directly to the patient while the other records information and helps set up intravenous fluid infusions and medications. In this fashion, there is always a nurse by the bedside. While this is taking place, the transfer of information between physicians and writing of orders can commence. Following this transition, the patient should then be approached in an orderly fashion to establish the level of function of various organ systems, to detect any urgent and critical problems, and to plan management for the period of recovery. (Refer to Table 1.)

### Table 1
Post-Operative Assessment

| I. Lesion                  | Pre-/post-operative anatomy (diagram)          |
|---------------------------|------------------------------------------------|
| Procedure                 | Procedure                                      |
| Anesthetic agents used    | Pressure measurements in OR                    |
| Complications             | Central lines                                  |
|                            |                                                |
| II. Vital signs           | Blood pressures                                |
|                           | (aortic, central venous or right atrial, left atrial, pulmonary arterial) |
|                           | Heart rate                                     |
|                           | Temp core                                      |
|                           | Respiratory rate                               |
|                            |                                                |
| III. CNS                  | Level of consciousness                         |
|                           | Pupils                                         |
|                           | Motor movement                                 |
|                            |                                                |
| IV. Respiratory           | Breath sounds                                  |
|                           | Ventilation                                    |
|                           | Spontaneous — describe pattern                 |
|                           | Controlled                                     |
|                           | Chest movement                                 |
|                           | Rate                                           |
|                           | FIO₂                                           |
TABLE 1—Continued

| TV | PIP | PEEP |
|----|-----|------|
| CXR—Lung fields |
| Mediastinal width |
| Heart size |
| ET tube position |
| Central lines |
| NG tube |
| Foreign bodies |
| Arterial blood gases |

V. CVS
| Heart sounds |
| Murmurs |
| Pulses—femoral |
| radial |
| dorsalis pedis |
| posterior tibial |
| Perfusion—capillary filling |
| temp feet |
| temp knees |
| Estimation of cardiac output (include pressure of mixed venous O₂) |
| EKG |
| Rate |
| Rhythm |
| Conduction |
| Vascular pressures |
| Pacemaker settings |
| Liver size |

VI. Fluids—patient's weight
| Intake—type, volume |
| Assessment of vascular volume |
| Electrolytes |
| Dextrostix |

VII. Hematologic system
| Clotting status |
| Hematocrit |

VIII. Medications
| Vasoactive drugs (quantity/wt/time) |
| PRN drugs |

IX. Plans

ASSESSMENT AND MONITORING

Cardiovascular System

The heart and circulatory system is clearly the focus of attention during the immediate post-operative period. In order to reduce the morbidity of the surgery, while permitting the patient to recover as rapidly as possible, there is a need to anticipate any circulatory compromise early and to augment cardiac function when ap-
propriate. We will first deal with the signs of cardiovascular compromise as it affects the circulation directly and as it affects the other major organs. Then we will cover the various approaches for enhancing cardiovascular function.

**Physical Signs** [4,5] There are numerous objective means for assessing cardiac function; unfortunately, the values and numbers generated by these methods are subject to error and there is enough biologic variability among patients that such data cannot be taken without reference to the physical examination. In order to understand and process the information obtained from a physical examination, it is helpful to be familiar with the changes that occur when cardiac output is compromised. When systemic perfusion is adequate, the child should be alert, breathing comfortably (at an age-appropriate respiratory rate), have warm extremities to the toes with good capillary refill, and normal peripheral pulses and blood pressure. When cardiac output is diminished, one of the earliest signs may include a slight increase in the heart rate as mediated through the release of systemic catecholamines. By the same token, these catecholamines serve to cause some peripheral vasoconstriction so that the most distal extremities are slightly cooler than normal with diminished capillary refill. There may also be a diminished urine output with concentration of the solute and a low sodium concentration. When cardiac output is further impaired, there will be a considerable increase in the heart rate, the patient may become restless, and peripheral vasoconstriction may be very obvious with cool extremities and very faint peripheral pulses. There may be oliguria and ileus at this point. By this time, respiratory rate usually increases (in response to a mild metabolic acidosis), and the respiratory pattern will depend on whether or not there is pulmonary edema or parenchymal pulmonary disease concurrent with the low cardiac output. When cardiac output is severely curtailed and shock is impending, the child may be agitated or somnolent, the trunk will be cool and the extremities cold and mottled, with faint or even nondetectable pulses of the peripheral extremities, with only femoral and carotid pulses palpable. The heart rate will be very rapid, simulating an atrial tachycardia (often mistaken for a tachyarrhythmia), the respiratory rate will be rapid, often with grunting, and there will be minimal urine output or anuria.

These physical signs are a result of the effects of diminished perfusion on various organ systems in combination with many of the humoral responses which serve to redistribute blood flow and to augment blood pressure and cardiac output. Predominant among these humoral agents are epinephrine, which serves to increase heart rate and contractility and has variable effects on systemic vascular resistance; norepinephrine, which serves to increase contractility and raise systemic vascular resistance, thereby helping to sustain blood pressure; angiotensin, which serves to raise systemic vascular resistance and stimulates the release of aldosterone, which then causes the retention of sodium, helping to maintain intravascular volume; antidiuretic hormone, which raises systemic vascular resistance and promotes retention of water; other agents, such as the prostaglandins and endorphins, may no doubt have very important roles in this process but at present these are less well identified.

With these considerations in mind, based on the physical findings, one should be able to discern much about cardiac output from a quick, but precise, physical examination. One should also pay very careful attention to signs of the state of intravascular volume. For most children, this means careful palpation of the liver. In the younger child fullness of the fontanel and in the older child distension of the jugular veins provide similar information. These signs are very useful when later deciding on appropriate therapy (cf. management).
**Bedside Hemodynamic Monitoring**  In line with the physical examination, it is necessary to have on-line monitoring in order to detect instantaneous changes in the cardiovascular function or to help interpret more subtle trends. Some types of information, e.g., the heart rate, are exceptionally useful for early warning signs, as alluded to above; other data, e.g., venous or atrial pressures, are more useful for interpretation of changes. Whatever the form of information derived in the electronic monitoring device used, one should be certain that specific criteria are recognized and met: all equipment should be properly calibrated and regularly checked; the data should be displayed for scrutiny at the bedside and, if possible, for printout; and alarms should be available that are adjustable to meet the changing status of the patient.

At the very least, an electrocardiogram with a cardiotachometer should be attached to the child and heart rate monitored continuously (with an alarm) until the child is completely stable and ready to be transferred to the regular ward. Usually the first objective signs of cardiovascular compromise in the child include either an acute increase or decrease in heart rate, although occasionally ectopy is the harbinger. One should also note whether the heart rate is relatively fixed and does not vary with stimulation; this may be indicative of a fixed tachyarrhythmia with A-V block, which in the case of a child may be at a rate quite comparable to a normal heart rate (it is very simple to stimulate the child gently to ensure that there is some variation in the heart rate).

The monitor is exceptionally useful in detecting gross variations in heart rate or in the electrical complex, but it is generally inadequate for the evaluation of a dysrhythmia. Whenever a question arises regarding the rhythm, one should listen to the heart sounds and simultaneously palpate a peripheral pulse. If the nature of the dysrhythmia is still unclear at this point, as it often is, one should then obtain recordings from multiple standard electrocardiographic leads, including those on the precordium and possibly even from pacemaker leads [6]. It is unfortunate that often the right-sided precordial leads yield the most amount of information regarding atrial rate but are easily overlooked because of bandages. It is worth the time and effort to try to obtain these. It may also be helpful to attach a direct atrial lead (if available) to the "V" lead, using tape or a metal clamp in order to obtain an atrial electrocardiogram. In light of this, if it is known prior to surgery that the child is susceptible to atrial and/or ventricular tacharrhythmias, temporary pacemaker leads make interpretation post-operatively considerably easier.

It is also essential to monitor blood pressure continuously in most patients. It is important to stress again that there may not be a decline in blood pressure early on when cardiac output is compromised due to peripheral vasoconstriction from the elaboration of catecholamines and other vasoactive hormones which help to maintain blood pressure (centrally). When there is intense peripheral vasoconstriction, the pulse pressure may be narrow and the diastolic decay may be relatively flat. These are more subtle signs and easily overlooked. In contrast, when there is a low blood pressure because of a compromised cardiac output, it may be one of the earliest signs to respond as therapy is instituted. Quite frequently, as intravascular volume is restored, blood pressure will transiently rise and then may fall again until additional fluid is given. Hence, blood pressure becomes a useful sign when trying to discern the response to therapy.

For most children after heart surgery, it may be necessary to measure blood pressure using an intra-arterial catheter connected to a system permitting continuous
display of the tracing. The catheter can be placed either percutaneously or by cut-
down into the distal artery of an extremity, provided there is good collateral circula-
tion. One should note that the transduction of the arterial pressure through a fluid-
filled system to an analog transducer and then to a digital recorder is subject to error
at many places [7]. First, if there is peripheral vasoconstriction, or obstruction either
within the distal artery or in the fluid-filled system, then the pressure recorded does
not accurately reflect central arterial pressure. It is important to observe blood pres-
sure tracings as well to note whether the tracing is overdamped (as occurs at very
high heart rates or with air in the system), or whether there is “fling” (the overshoot
of a tracing at the peak or ebb of pressures that occur with an underdamped system).

In a patient breathing spontaneously, it is the convention to record blood
pressures at end-expiration; when these values are recorded with reference to at-
mosphere (as is the standard method for calibrating the equipment), the values are
usually slightly higher than the pressures during inspiration [8]. As is well known,
processes such as pericardial tamponade accentuate these inspiratory/expiratory dif-
ferences [9,10]. When a patient is breathing with positive pressure ventilation, the
pressures (again referenced to atmosphere) may increase slightly during inspira-
tion, particularly if there is a high inspiratory pressure; under these conditions, there is no
“correct” value to record, but it is important for the staff to be consistent when
following these values in serial fashion. There is no value in taking the patient off
positive pressure ventilation transiently to try to get more reliable values, and such a
maneuver may have significant hazard to the patient who is unstable.

Since there are potential hazards from the use of intra-arterial catheters, they
should be removed when it is deemed that the patient is stable and continuous blood
pressure monitoring unnecessary [11]. For the most part, they should not be used
just as a source of routine blood drawing. Embolism from a peripheral arterial line
usually does not have the same life-threatening risks as it might from a left atrial
line. On the other hand, it is important to note that in the infant or in the subject
with a very low cardiac output, it is quite possible to flush debris or air retrograde,
particularly from the arm into the cerebral circulation. A rapid flush by hand may
easily exceed the blood flow through the radial artery.

Some measurement of the change in filling pressure of the ventricles may be useful
in the patient with extensive surgery. For the left ventricle, filling pressure may be
best approximated by the mean pressure in the left atrium or with a catheter in the
pulmonary capillary wedge position. Left ventricular end-diastolic pressure is less
well estimated by the pulmonary arterial diastolic pressure or the right atrial pres-
sure. For the right ventricle, the end-diastolic pressure may be estimated best from
the right atrial or central venous pressure (recall that changes in central venous pres-
sure may also be detected by changes in the size of the liver, or in the fullness of the
fontanel or jugular veins). With any of these means of monitoring filling pressure,
one should be sure that there is no obstruction between the site of monitoring and
the particular ventricular chamber of interest. As an example, when there is pulmo-
nary vascular obstructive disease, pulmonary arterial end-diastolic pressure
will be significantly higher than the left atrial pressure and left ventricular end-
diastolic pressure, and therefore not reflect the true value of the filling pressure of
the left ventricle. Moreover, although we translate changes in filling pressure to
changes in end-diastolic volume, there are numerous factors that shift the pressure
volume relationship of a ventricle, confounding this relationship. Normally, as end-
diastolic volume rises, so does end-diastolic pressure. However, if pressure around
the ventricle or atrium is significantly elevated, as occurs with the presence of fluid or air in the pericardium, mediastinum, or pleural space, the pressure in the atrium may also be elevated (with respect to the atmosphere) and not reflect a large filling volume. The classic example of this is pericardial tamponade [10]. This error would be avoided if pressures within the ventricles were referenced to the pressures immediately outside the chambers, but this is impractical. As important, and considerably more subtle, the pressure volume relationship of a ventricle may be affected by the neighboring ventricle. For example, in the presence of right ventricular distention, end-diastolic pressure in the left ventricle may be elevated without a comparable rise in volume [12,13]. Elevations in right ventricular afterload (as occurs with positive pressure ventilation or pulmonary vascular disease) causing an increase in right ventricular volume can easily produce this phenomenon. Thus, in the interpretation of the filling pressures one should consider other pathophysiologic conditions occurring concomitantly; both the physical examination and an echocardiogram may help clarify these situations. The echocardiogram is a particularly important adjunct to interpretation of filling pressures when there is concern that the pressure volume relationship of the ventricle may be altered. In addition to detecting such factors as pericardial fluid surrounding the heart, the echocardiogram is very sensitive to changes in size of the left atrium or left ventricle and the position of the ventricular septum.

Albeit an exceptionally useful form of monitoring, central pressure catheters carry major risks of embolization of air or blood clots. For a catheter in the left atrium or a catheter in the systemic venous circulation, in the presence of a right-to-left shunt, one must be aware that air embolism to the coronary or cerebral circulations may easily occur if the lines are not handled meticulously and kept free of bubbles. Air filters help reduce the risk but certainly do not eliminate it. It is imperative, therefore, to use these lines only when less invasive means for monitoring patients will not suffice and to recognize that when these catheters are clotted or malfunctioning, they should be immediately attended to.

As with the arterial catheters, values are usually recorded from central venous catheters at end-expiration in the spontaneously breathing subject. No convention exists other than the need for consistency when the patient is on positive-pressure ventilation. All measurements should be made at mid-chest level, and it should be realized that apparently small differences in the positioning of the transducer can introduce substantial error in interpreting the data since one is only dealing with a difference of a few millimeters of mercury. Since end-diastolic pressures of both ventricles tend to increase with age, there is no single set of values which represents the normal for all subjects. Moreover, since ventricular compliance is a major determinant of the optimal filling pressure, even with subjects at a given age it is difficult to say exactly what the appropriate end-diastolic pressure should be.

The ultimate concern when collecting cardiovascular data is whether the cardiac output is sufficient to meet the metabolic demands of a patient. To determine this, the physical examination and the objective data should be put together to ascertain the status of the child. No one set of numbers alone suffices. When one is satisfied that perfusion is adequate and the patient is stable and comfortable, then limits can be set for blood pressure, heart rate, filling pressures, and the like, for which one should be alerted, and recovery can commence. On the other hand, if the findings indicate that the systemic perfusion is not sufficient, one may want to quantify cardiac output directly and institute additional therapy as is outlined later in the paper.
Following this initial assessment of the child's cardiovascular function, a more detailed physical examination should be done and assessment of the other major organ systems undertaken.

**Central Nervous System**

Upon return from the operating room the child may not be awake, alert, and moving about since it may take time for anesthetic agents and muscle relaxants to be metabolized and excreted, particularly if the patient is still cool from hypothermia or if cardiac output is low. Because of this, very limited information about the neurologic status can be obtained initially, and neurologic problems may be easily overlooked, particularly in young infants with whom there are only limited lines of communication even after the child becomes more alert. An examination should include the level of consciousness (the use of the Glasgow score may be helpful), an assessment of brain stem reflexes (e.g., pupillary responses to light, doll's eyes, or even cold caloric responses, if necessary), gross motor responses, and the detailed notation of any drugs which may interfere with central nervous system function. (N.B.: Both belladonna alkaloids and opiates affect pupillary size, and both should be charted.)

Once the child has apparently normal perfusion and normal body temperature, if there is still no spontaneous movement or a diminished level of consciousness, one should first ensure that the muscle relaxants are fully reversed. This may be done by administration of an appropriate anticholinesterase agent, if non-depolarizing muscle relaxants (e.g., curare, pancuronium) were used, and then tested with a nerve stimulation device. If the altered level of consciousness was thought due to narcotic agents, it is often best to let the drugs be metabolized rather than to use narcotic antagonists. Antagonism of a narcotic agent may have fairly substantial effects on the cardiovascular system and produce sudden hypertension and/or tachycardia, neither of which may be desirable. Clearly, the child who remains flaccid and unresponsive with no obvious cause needs additional evaluation urgently.

The children who are at the highest risk for neurologic complications both before and after heart surgery include: those who have intracardiac right-to-left shunts, since they have a potential for systemic embolism via the shunt [14]; those children who are in a low cardiac output state, since they are susceptible to cerebral hypoperfusion and ischemia; and those children who need to be given muscle relaxants and heavy sedation for management post-operatively, since they have a limited ability to respond to problems. Each of these groups of patients should be watched exceptionally carefully, and routine neurologic signs should be recorded.

**Respiratory System**

The respiratory system is frequently compromised as a consequence of impaired cardiovascular function and cardiac surgery. All aspects of pulmonary function may be affected—particularly mechanics and gas exchange, but even metabolic activity [15]. The children who are at the greatest risk for respiratory compromise are those who have excessive pulmonary blood flow and pulmonary hypertension (as with a ventricular septal defect), or those who have a complicated and prolonged intraoperative course [16,17]. Both of these groups of children frequently have copious, thick secretions, pulmonary edema (both alveolar and interstitial), and alveolar, and possibly lobar, collapse. Each of these factors tends to cause a fall in lung volume and a marked decrease in lung compliance, thereby making positive
pressure ventilation or spontaneous breathing more difficult. These problems may be exacerbated by the presence of cardiomegaly, since an enlarged left atrium and/or hypertensive pulmonary arteries may compress large bronchi, thereby causing emphysema of a lobe and eventual collapse [18]. Another particularly difficult group of patients to manage are those in whom pulmonary blood flow is excessive to one lung and diminished to the other. This may occur when there is an aortopulmonary shunt to one lung without an augmentation of blood flow to the other. A lung with high pulmonary blood flow may become edematous and noncompliant, whereas the other lung is much more supple. With positive pressure ventilation, gas flow tends to go to the more compliant lung while the blood flow is predominantly going to the less compliant one. This leads to severe ventilation perfusion imbalance and often to the creation of very high dead space ventilation. There is no satisfying medical therapy for this condition, and further surgery is often necessary [16].

After any prolonged cardiac surgical procedure, patients develop some degree of atelectasis and pooling of the secretions. Muscle relaxants, narcotics, hypothermia, and the presence of an endotracheal tube may depress the cough, interfere with mucociliary action, and diminish clearance of secretions. Post-operatively, mechanical ventilation should be continued until the patient has a cough, is alert enough so that secretions can be cleared, and has reached normal body temperature.

Many children, because of an unstable cardiovascular system or more significant respiratory problems, may need more prolonged mechanical ventilation. In these patients the endotracheal tube needs to be well secured to avoid extubation or tracheal damage. The ventilator should be adjusted so that the patient is receiving a breath at least as deep as that produced by hand ventilation. Generally during the first post-operative day (except in the case of premature infants or in the presence of residual right-to-left intracardiac shunts) the inspired oxygen concentration is usually adjusted so that the patient has near fully saturated hemoglobin (PO2, 100–150 mmHg) and remains well oxygenated at all times. It is quite easy, particularly if cardiac output is low, for arterial oxygenation to plummet in a short period of time, thereby rapidly leading to hypoxia. The patient who has had heavy sedation or muscle relaxant has no ability to respond to this situation by increasing ventilation. Later, if prolonged mechanical ventilation is necessary, a lower inspired oxygen concentration may be appropriate because of the long-term risk of oxygen toxicity.

In addition to watching and listening to see if the patient is being ventilated, one should have an idea of the ease with which the child's lung can be expanded (lung compliance). This is best done by hand ventilating the patient and observing chest movement. Following this procedure, one should again observe the patient breathing with mechanical ventilation, paying specific attention to: (1) the observed breathing pattern; (2) the breath sounds, particularly at both axilla; (3) the type of ventilation (controlled, intermittent, mandatory ventilation, and so on); (4) the specific ventilator settings (rate, inspired oxygen concentration, tidal volume, and inspiratory and end-expiratory pressures); and (5) at what level the alarms are set. A chest X-ray taken in the post-operative period is also very helpful. One should note particularly the nature of the lung fields and depth of lung expansion, the heart size and mediastinal width, particularly in comparison to previous films, and the position of the endotracheal tube, central lines, chest tubes, and any other intravascular or intrathoracic foreign bodies.

The aim of mechanical ventilation is ultimately to provide adequate gas exchange. Although auscultation and chest movement serve as guides, the adequacy of ventila-
tion must be confirmed by the measurement of arterial blood gases. These may need to be followed frequently, at least as often as hourly, until the child is hemodynamically stable following surgery. Measurements should continue to be obtained on a regular, although less frequent, basis until the child is breathing spontaneously. These data provide immediate feedback and their usefulness is markedly diminished if there is a long delay before the results are available.

Many intensive care units are now equipped with the ability to measure skin surface PO₂ and even PCO₂ [19]. These devices are helpful for continuous monitoring in an unstable patient or when an indwelling arterial line cannot be used. On the other hand, in the presence of impaired peripheral perfusion, the surface PO₂ correlates poorly with central aortic PO₂ and one may be easily misled without measuring arterial PO₂ directly. When the child is more stable, particularly if there is a need for prolonged mechanical ventilation, these devices may be of the greatest use.

Any aberration of blood gases certainly demands immediate attention, since this indicates potential compromise of ventilation, circulation, or both. Whenever there is persistent hypoxemia and the cause is not obvious, it may be helpful to measure blood gases from a mixed systemic venous blood sample and a left atrial blood sample, as well as an arterial blood sample. Using the mixed systemic venous sample and arterial blood sample with a knowledge of the inspired oxygen concentration and hemoglobin concentration, the percentage of right-to-left shunt may be quantified in the standard shunt equation [20]. Comparison of the left atrial blood sample with that in the aorta may help to discern whether the shunt is of pulmonary or cardiac origin; for example, if the left atrial blood sample is equivalent to a calculated ideal pulmonary capillary blood sample whereas the aortic sample has a much lower oxygen concentration, it suggests that there is right-to-left intracardiac shunting. If, on the other hand, the left atrial PO₂ is well below that of the pulmonary capillary value, it suggests that there is right-to-left intrapulmonary shunting. There may, of course, be both intrapulmonary and intracardiac shunting, in which case the pulmonary capillary PO₂ will be higher than the left atrial PO₂, which will be higher than the aortic PO₂. It may be difficult to quantify the exact amount of these shunts because the left atrial sample is not really well mixed. Equally useful for detecting intracardiac shunts is an echocardiogram with an injection of a contrast material such as saline into a central vein or the right atrium [21]. The immediate appearance of contrast on the left side of the heart suggests that there is a right-to-left intracardiac shunt. Again, this may only provide qualitative information but can be very helpful in discerning the level of the shunting.

Hematologic System

During the post-operative period two problems related to the hematologic system are of particular concern: blood coagulation and blood replacement [22]. Patients who are at greatest risk for abnormalities of blood coagulation include: (1) those children who have been chronically cyanotic and polycythemic pre-operatively, since they have nonspecific coagulopathies which do not immediately correct themselves; (2) children who have prolonged cardiopulmonary bypass, since they have poor platelet function and often incomplete reversal of anticoagulation; (3) patients who are cold and poorly perfused, since they may not metabolize anticoagulants readily and are prone to intravascular coagulation. It is particularly difficult to judge the amount of reversal of heparin therapy necessary in a patient who is cold and poorly perfused. Generally, 1 mg of protamine can be given initially over five minutes to
Renal conditions may affect the circulation. The presence of an increased cardiac output [25] results in these values doing service as sensitive guides as they help in increasing intravascular volume and thereby in decreasing the need for blood replacement. Stored bank blood is deficient in clotting factors and platelets, both of which may be necessary to give the patient if bleeding continues. Any patient who has a persistent inability to form a blood clot after body temperature has increased to normal needs further assessment of coagulation. One should be particularly aware of the factors alluded to above. When possible, blood should be directly removed from a vein into a nonheparinized syringe for evaluation of clotting status. If perfusion is poor, this may not be readily accomplished, and one can remove blood from an arterial line, attempting to clear it of heparin first by withdrawing blood in a volume in excess of the dead space of the line. This is no guarantee that all heparin is removed, but may have to suffice for initial assessment.

There may be a considerable amount of blood loss during the post-operative period due to blood sampling for laboratory studies, in addition to the obvious loss of blood through chest tubes and the more subtle sequestration in the mediastinal space. It is essential to keep an accurate blood balance, particularly in the small child. This should at least be calculated on an hourly basis until the chest tube drainage is minimal, and often in the presence of extensive blood loss, balance should be computed more frequently. In addition, a hematocrit should be obtained on a regular basis until blood replacement is unnecessary. Although the hematocrit is less sensitive to changes in blood volume, it helps in the decision as to which type of solution should be used for replacement.

If massive blood transfusion is necessary, there is a large load of acidic blood which can cause a substantial decrease in blood pH until the citrate is metabolized; then there will be alkalemia. However, metabolism of the citrate may be impaired or slowed if liver function is compromised. In addition, stored bank blood contains agents which chelate calcium and therefore, in the smallest children, calcium gluconate should be given with blood replacement in roughly a ratio of 1 mg calcium gluconate to 1 cc of blood transfused. Lastly, if large amounts of platelets or blood need to be transfused, aggregates can form in the lung and thereby impair gas exchange and possibly other functions of the lung [23].

Renal System

The kidneys respond to a low cardiac output by retaining sodium and water, thereby helping to increase intravascular volume and restore cardiac output toward normal. Therefore, the urine flow and sodium concentration in the urine are often sensitive guides as to the status of adequacy of circulation [24]. On the other hand, these values do not necessarily reflect the intravascular volume; for example, in the presence of an expanded intravascular volume and high ventricular filling pressures, urine volume may be low and sodium concentration low because of an inadequate cardiac output [25]. These values are more sensitive reflections of renal plasma flow than they are of intravascular volume. One should also be aware that many agents or conditions may alter the urine composition and volume, relatively independent of the circulation. Diuretics tend to increase both urinary volume and sodium concentration (for a variable period of time) [26]. In the post-operative period, there is also often a large diuresis due to the saline load resulting from hemodilution during cardiopulmonary bypass, and the osmotic load from glucose and mannitol [27]. As body temperature returns to normal and glucose homeostasis is restored, the urine...
output may also decrease, and there will no longer be reducing substances present. At this time, the urine flow may again reflect the circulatory status.

When the serum creatinine is near normal and the urine output is in the range of \( \frac{1}{2} - 1 \) cc/kg/hour in the post-operative period, it suggests that renal perfusion is adequate. However, a higher urine flow is usually desirable. Since there is often some degree of hemoglobinuria following cardiopulmonary bypass, a urine output more in the range of 1–2 cc/kg/hour may help to avoid the possibility of stasis within the tubules and subsequent damage. If there is macroscopic evidence of hemoglobinuria, a forced diuresis should be maintained using both mannitol and fluid, so that urine flow can be maintained without compromising intravascular volume.

Whenever the urine output is inadequate, further investigation is warranted immediately—not just because of the potential for renal damage, but because of the implications for the adequacy of the systemic circulation. The approach should be tailored to the particular problem. Volume depletion or a low cardiac output result in a concentrated urine and low urinary sodium content. Here, the physical examination with particular attention to the central venous pressure or liver size may help to distinguish the cause. If there has been a period of substantial hypotension or significantly compromised cardiac output, oliguria may be a sign of impending renal failure. In this case, although urine volume is low, there may be wasting of sodium in the urine and an inability to concentrate solute. Occasionally the sediment may also be abnormal. Finally, urine output may be low due to inappropriate secretion of antidiuretic hormone. Here, urine will be concentrated (serum osmolality will be less than urine) with an elevated sodium content due to intravascular volume expansion. Central venous pressure may be helpful in confirming this.

With the above considerations in mind, it is exceptionally helpful to monitor urine output on an hourly basis, using a catheter in the bladder in all but the most stable of patients. Additionally, urine should be routinely checked for sugar, protein, specific gravity, and blood (and hemoglobin, if there is blood present). In the patient who is oliguric without clear cause, one should first be certain that the catheter is not obstructed. Then it may be helpful to examine the urine sediment and to measure urinary and serum sodium, creatinine, and osmolality, remembering, however, that if there is diuretic present (including glucose), this will confound any interpretation of the urinary sodium and osmolality. In the absence of diuretics, such an approach may help to detect whether the low urine output is due to renal failure, prerenal compromise, or high levels of antidiuretic hormone.

**Metabolic Function**

The child who undergoes cardiac surgery with cardiopulmonary bypass is subject to numerous metabolic derangements post-operatively. The small child with a large surface area-to-weight ratio may very readily lose heat when undraped and may warm up slowly, particularly if cardiac output is low [26]. The problem is even more significant in the small infant in whom deep hypothermia was used. A cold patient fails to metabolize drugs normally and may also have abnormal uptake of drugs given intramuscularly. Core temperature and skin surface temperature should be monitored continuously. Toe temperature has been used as an index of peripheral perfusion, and temperature of the skin surface over the trunk is also helpful to adjust overhead heating devices [27].

Following hemodilution and cardiopulmonary bypass, there are usually marked shifts of fluid in the body compartments and an increase in the total body water,
much of which is extravascular. It is virtually impossible to know what a child's exact fluid status is until body temperature has returned to normal. Such a judgment is also complicated by the large losses of urine initially, the loss of fluid through chest tubes, the excessive insensible water losses in the small patient exposed to the atmosphere and an overhead heater, and the mobilization of excess water over the few days following cardiac surgery. Regardless of these difficulties, every attempt should be made to keep a careful balance of fluid, including all sources of measurable fluid loss, a rough knowledge of composition of this fluid, and a net balance on an hourly basis until fluid losses return toward normal.

In addition to the redistribution of fluid, electrolyte homeostasis may also be altered. The most important change seems to be the loss of potassium. This is exacerbated if the child has been on chronic diuretic therapy and the serum chloride is also low. Despite marked shifts or loss of potassium, potassium replacement is usually not essential initially since much potassium is provided by blood transfusion. However, some conditions may warrant potassium replacement: (1) if the serum potassium is very low (in the range of 2.5 meq/L), (2) if there are dysrhythmias, or (3) if the patient is receiving a digitalis preparation or has been on one up until the time of surgery. Of even more importance is hyperkalemia, a potentially life-threatening problem. Although the problem may be worsened by oliguria or hemolysis, it is usually in the setting of poor perfusion and acidosis that hyperkalemia becomes a menace and needs urgent attention. With an adequate cardiac output the rise in serum potassium is usually slow. Because of the possibility of electrolyte derangements also, particularly when acid-base status is not normal, serum electrolytes should be followed on a regular basis until the patient is stable and on an oral diet.

Glucose homeostasis may also be impaired post-operatively [28]. There is a relatively large glucose load provided from the fluids in transfused blood, and if the child is cold, glucose will not be utilized properly. In addition, hyperglycemia may be present because of the effect on glucose homeostasis of the high levels of circulating catecholamines. With time, serum glucose may drop precipitously because of the excessive urinary losses and exhaustion of body stores of glucose. This is a particularly important problem in the patient who has been in chronic congestive heart failure and is cachectic or in the patient who is receiving intravenous catecholamines. Because of this, blood glucose should be monitored frequently by one of the clinically available bedside methods in all infants (particularly those who have been malnourished) until they are receiving adequate nutrition.

**MANAGEMENT**

*General Care*

Once the child has been initially stabilized, assessed, and examined, clear plans for initial management can be developed. In addition to care related directly to the cardiovascular system, other general concerns as mentioned earlier (including fluid balance and metabolic function) need immediate attention. The patient should be kept in near neutral thermal environment, since thermal stress will raise the demands for cardiac output [30]. For the young child this may necessitate an overhead warmer, whereas in the older patient a blanket may suffice, although neither method will be particularly efficient if cardiac output is low.

Glucose may be the only source of calories initially and should be provided to all patients liberally until other nutrition is available. All patients need at least 20 percent of their basal caloric expenditure provided in the form of glucose. For the
young infant (less than 10 kg) this should be at least 4–5 g/kg/day of glucose. Since the patients are usually not receiving full maintenance fluid, they may require 10 percent glucose solutions for short periods of time. When the patient's recovery is not smooth and oral intake is delayed more than a few days, serious consideration should be given to providing additional nutrition. Enteral nutrition is generally preferable to parenteral route because of safety, but it is common for there to be ileus for a few days post-operatively and during this time a nasogastric tube is necessary. Later, when bowel sounds are heard, enteral feeding can be started. In the infant, it is safe to place a small amount of formula down through a nasogastric tube and check residual gastric volumes. As long as the patient is not agitated or distended, the risk of aspiration is low, particularly if the nasogastric tube is left open to atmosphere rather than clamped.

It is very difficult to calculate precise fluid needs for children who have been on cardiopulmonary bypass since there may be a considerable amount of fluid accumulated in extravascular spaces, and with hypothermia there may be considerable peripheral vasoconstriction. Initially, it is simplest to provide approximately one-half the usual maintenance fluid requirements. This will provide enough fluid for insensible water losses and can be given as dextrose in water. In the child who has not been on cardiopulmonary bypass, usual maintenance fluids are appropriate [29]. One should be particularly cautious not to fluid-restrict the patient who has significant hypoxemia post-operatively, particularly if there is concurrent polycythemia, since this may predispose him to vascular accidents. Sufficient electrolytes are usually provided from the blood transfusions and saline in various monitoring lines. If potassium needs replacing, as discussed previously, approximately 0.2 meq/kg/hour can be given intravenously and repeated one or two times. It is often preferable to place just one hour's worth of potassium-containing solution in the intravenous fluid reservoir so that an additional amount is not inadvertently given. When body stores of potassium have been severely depleted, replacement may take many days. In this setting serum potassium may transiently rise after an intravenous bolus and then fall within a short time, making exact replacement difficult to judge. Later in the post-operative course, potassium replacement may be given with feeding by using foods rich in potassium, formula with a relatively high potassium concentration, or, on occasion, supplementing the feeding with potassium chloride (this is the least useful since it often causes gastric irritation).

In addition to the crystalloid given, there is also a need to replace most or all of the ongoing plasma and blood losses from chest tube drainage, dressings, blood sampling, and so on. The particular choice of fluid depends on that which is presumed to be lost. When there is active bleeding or poor clotting, packed red blood cells and fresh frozen plasma can be given; when proteins are lost or are low, colloid can be used; if the hematocrit is low (less than about 30 percent), packed red blood cells can be given; if the hematocrit is in the range of about 30–45 percent, whole blood or colloid can be used; and if the hematocrit is greater than 45 percent, colloid or crystalloid is usually appropriate. Usually, maintaining a hematocrit in the range of 35–40 percent is adequate. However, if the child has a persistent right-to-left intracardiac shunt with hypoxemia, it may be desirable to maintain him with a hematocrit in a slightly higher range (closer to 50 percent).

Respiratory Care

Respiratory management very much needs to be tailored to the particular patient, and no simple algorithm can be applied to all children. Some patients may be ex-
tubated in the operating room or very shortly thereafter. These are usually children who have the more simple surgical repairs, who have not been on cardiopulmonary bypass, and who are very stable hemodynamically. Others, such as those with pre-operative pulmonary edema, major intraoperative complications, or prolonged cardiopulmonary bypass, may need mechanical ventilation for a variable period of time [30]. There are numerous ventilators available for this purpose, each with its unique characteristics. As a common starting point for instituting mechanical ventilation, certain general guidelines may be used. Initially, it is safest to hand ventilate the child to see how easy it is to move his chest and provide adequate air entry. If the child has a cuffed endotracheal tube, then it is reasonable to set the ventilator to a tidal volume in the range of 10–15 cc/kg initially. If there is no cuffed endotracheal tube, one may set the ventilator for a similar tidal volume or, if it is a pressure-limited ventilator, to an inspiratory pressure approximately equal to that developed with hand ventilation. Whether using a cuffed or an uncuffed endotracheal tube, it is essential to observe chest movement as soon as the patient is connected to the ventilator and adjust tidal volume accordingly. The ventilator rate used initially varies, certainly depending on what blood gases were obtained toward the end of the procedure, and depending on the child's age. Generally a rate in the range of 10–15 breaths per minute for the older children and 15–20 breaths for younger children are appropriate places to start. Initially, inspired oxygen concentration should be 100 percent and one may want to use a small amount of end-expiratory pressure, 2–3 cm H2O. The administration of positive end-expiratory pressure clearly can have effects on circulatory as well as respiratory function. These potentially adverse effects are well described and should be considered whenever positive pressure breathing is necessary on a patient with cardiac disease [16,17,31]. Specifically, in patients with very low pulmonary artery pressure and/or blood flow, end-expiratory pressure needs to be used cautiously, since it can potentially raise pulmonary vascular resistance and impede cardiac output. Once this pressure is established, ventilation can be adjusted based on the blood gases. If blood gases show marked venous admixture initially, three factors should be quickly investigated: (1) it is easy for the endotracheal tube to slip into a main stem bronchus with transport and this should be rechecked, (2) secretions often pool and suctioning may need to be done, and (3) tidal volume may be inadequate.

Following this initial management, respiratory care of the post-operative patient is not unique and can be guided by the same general principles of mechanical ventilation of most other patients. In the case of the child with heart surgery, however, one should have in mind the plans for cardiovascular management and any other potential complications. It is unwise to begin weaning a patient who is hemodynamically unstable. Additionally, if it is planned to try to extubate a child in the morning after surgery, there may be no need to wean ventilator support through the night since it may be done relatively rapidly in the stable patient.

Much has been written about weaning from positive pressure ventilation and numerous criteria have been developed for adult patients [32]. Although it is more difficult in small children to obtain exact data regarding lung mechanics, one should still be certain that a child meets certain criteria prior to extubation [33,34]. These include: (1) adequate control of ventilation—note the arterial blood gases while the patient breathes spontaneously (some patients with a metabolic alkalosis may maintain a relatively normal pH while PCO2 is elevated, and this does not imply impaired control); (2) ability to protect the airway and clear secretions—check whether the gag and cough are adequate; (3) patent upper and lower airways—inspect the chest
X-ray and watch the breathing pattern while the patient breathes spontaneously; (4) the mechanical capacity to take deep breaths and respire without great effort—observe while the patient breathes spontaneously (consider fluoroscopy if there is any concern for phrenic nerve function); although a patient may be able to take a deep breath, if this is with great effort it will cause excessive energy expenditure and rapidly lead to tiring in the absence of ventilatory support [35]. One should also guarantee that there will be adequate oxygenation within inspired oxygen concentration no higher than 40 percent since it is often difficult to provide a consistently higher inspired oxygen concentration when the child is extubated [36]. If it is anticipated that the child will have some difficulty maintaining ventilation when extubated it may be helpful to correct any anemia and to provide adequate nutrition prior to weaning from mechanical ventilation.

Once the decision is made to begin weaning the patient from positive pressure ventilation, the speed with which this is done and the method very much depend on the patient's clinical status. Children who are very stable with good mechanical function of the lungs may be weaned rapidly as soon as they are alert. For other children, the process may be very slow and require days to accomplish. There is no need to stress the patient during the weaning procedure and it is beneficial, if possible, to keep arterial blood fully saturated with oxygen so that any sudden change in ventilation does not result in hypoxia.

Immediately following extubation the child still remains at high risk; any signs of respiratory distress, including retractions, tachypnea, agitation, hypoxemia, or apparent fatigue, warrant immediate attention and consideration of reintubation. If the child is in distress, attempts should be made just to make the child more comfortable and position him so that the work of breathing is minimal. Often sitting a child up or relieving gastric dilatation in an infant may accomplish these goals. However, disappointment because of apparent failure to keep a patient extubated should not cause one to observe a child who is tiring too long. It is much safer to reintubate the patient under controlled conditions in which he can be pre-oxygenated and given appropriate sedation rather than in an emergency fashion.

**Inadequate Perfusion**

When the patient's recovery is not smooth, perfusion is inadequate, or it seems necessary to augment cardiac function, two general considerations are necessary. Can demands for blood flow be lowered? Can the cardiac output be increased? Careful attention should be paid to factors that may be increasing demands for blood flow above basal levels. These include thermal stress (either fever or an environment that is not close to the neutral thermal range), anemia, hypoxemia, agitation, and excessive work of breathing. Whenever possible, these factors should be reduced or eliminated; this may even entail reintroducing positive pressure ventilation. At this point, if there is still a need to augment cardiac output, each of the determinants of cardiovascular function should be assessed as well as possible in order to determine an appropriate course for therapy. Very quickly, the heart rate should be checked. Some estimate should be made of whether cardiac filling is high, low, or normal; this may include factors from physical examination as well as right or left atrial pressures, and, if necessary, an echocardiogram. There is no clear measurement of afterload, but one should measure the blood pressure, examine peripheral pulses to see if the patient is vasoconstricted, and look at the contour of the blood pressure trace if there is an intra-arterial catheter. Contractility is not readily assessed by a single value, however; one should see whether the upstroke of
the arterial trace is brisk, feel whether the precordium is active, feel the nature of arterial pulses, and again consider the use of an echocardiogram to examine ventricular wall motion.

An insufficient filling volume may often be the cause of poor perfusion in the early post-operative period and should be considered soon. As body temperature increases following cardiopulmonary bypass or after exposure to a cold operating room, there may be marked vasodilatation and the need for restoration of intravascular volume. The fluid requirement in these cases may be very large and continue for hours. It may be further exacerbated by ongoing fluid losses into the chest tube, the interstitium, and insensible losses. In addition to fluid loss and an increased venous capacity for fluid, one should also consider factors that may impede cardiac filling despite an adequate intravascular volume. Fluid or air under pressure in the pericardium, mediastinum, or pleural space will tend to raise atrial pressure (with respect to the atmosphere) but will impede filling. Clearly, these need to be treated directly.

In the presence of significant volume loss, fluid (usually containing colloid) may be given by bolus in quantities of at least 5–10 cc/kg over a few minutes, while watching the blood pressure, heart rate, and filling pressure. Once the fluid is given there is usually a rapid response with a rise in blood pressure, if it was low, a slowing of heart rate, and an increase in peripheral perfusion and possibly even urine flow. This response may be transient, signalling the need for more fluid therapy. It is difficult to choose an exact value for filling pressure at which to stop giving fluid; one may be left finding a level range at which perfusion seems adequate and then trying to maintain this while checking the physical exam frequently. Usually it is not advisable to exceed a left atrial pressure of 15 mmHg, since this can cause fluid accumulation in the lung; however, there are exceptions to this limit, such as when a patient is being ventilated with very high end-expiratory pressures.

Generally, an increase in the heart rate is the child's first defense against a low cardiac output. There is nearly a linear relationship between heart rate and cardiac output through a wide range in the child, and cardiac output may continue to increase until heart rate approaches 200 or more in the newborn and very young infant. The younger the child, the higher is the normal resting heart rate; for newborn children this may be in the range of 120–160 beats per minute.

Usually it is not necessary to increase the heart rate pharmacologically because the presence of sympathetic stimulation (neural and humoral) when cardiac output is low raises the heart rate. However, patients who have been on digitalis, who have significant myocardial damage, who have an intra-atrial conduction defect, or who have been chronically ill and malnourished, may not have an appropriate heart rate response to a low cardiac output. Heart rate can be increased by anticholnergic agents (such as atropine), adrenergic agents (such as isoproterenol), or by means of a pacemaker, if leads are available. In an emergency situation atropine may be the quickest agent available and then a continuous infusion of isoproterenol or pacemaking can be instituted.

More common than the problem of a low heart rate, a tachyarrhythmia may occur and interfere with cardiac output. Frequently, this is precipitated by hypoxemia, acidemia (causing hyperkalemia), or low cardiac output. In fact, in the presence of a low output it may be difficult to determine what was the exact inciting cause. Before starting therapy, one should first determine the type of dysrythmia present from an electrocardiogram and then quickly decide whether the patient is in impending shock. Tachyarrhythmias which cause cardiovascular collapse demand immediate
therapy—oxygen, correction of acidosis, support of the circulation, and electrical or pharmacologic conversion. When a less life-threatening dysrhythmia occurs, pharmacologic therapy alone may be more appropriate once all the potentially inciting factors are reduced or eliminated [37]. It is important to stress that a sinus tachycardia in response to a low cardiac output in the child may easily simulate a tachyarrhythmia. In the former, there will usually be some variation in the rate and possibly “p” waves may be seen in some of the leads (often right-sided precordial leads or lead II) if a fast paper speed is used or if vagal tone is increased. Here, treatment should be directed toward improving cardiac output by other means rather than by trying to “convert” a tachycardia. One should also remember that other factors may precipitate a sinus tachycardia that are easily overlooked—these include fever, hypoglycemia, agitation, and pain.

Although myocardial contractility in the child is often surprisingly good despite extensive surgery, there may be impaired inotropic function when there has been damage or resection of ventricular muscle, or when the child has been in chronic congestive failure pre-operatively. Children who undergo a Rastelli-type procedure [38] or those who have muscle resection because of outflow obstruction are most susceptible to impaired ventricular function.

If it is necessary to improve contractility, a number of agents with potent inotropic effects can be used [39,40]. All increase myocardial work and oxygen demands to some extent when they augment cardiac output, and each has its own risks. Generally, it is preferable in the immediate post-operative period to use medications which have a relatively rapid onset, rapid metabolism, can be titrated to a response, and are relatively safe even in the presence of electrolyte imbalance. These are important concerns when a patient is unstable, since the response to therapy is uncertain, urine output may be highly variable, perfusion of metabolic organs is impaired, and there are concomitant fluid and electrolyte problems. Thus, digitalis preparations tend to be less useful under these conditions than the intravenous sympathomimetic drugs. On the other hand, digitalis may be valuable as an antiarrhythmic agent. When one is ready to start an inotropic agent, it is useful to ensure that glucose and calcium are adequate. It is often helpful to provide them on a continuous basis until the patient is stable. If the heart rate is low, it may be desirable to choose an agent with both chronotropic and inotropic effects, such as isoproterenol. Dopamine has the potential benefit of increasing renal blood flow, although in high doses it also increases systemic vascular resistance, which can increase the load on the myocardium. Otherwise, there is an expanding list of drugs and the choice may be made by personal preference. The three sympathomimetic agents in most common use, isoproterenol, dopamine, and dobutamine all share the potential for inciting rhythm disturbances, especially in the failing heart. This problem may necessitate adding an antiarrhythmic agent, decreasing the dose, or altering therapy. It is also often necessary to switch medications or add another medication if the initial response is insufficient. Nevertheless, whenever a medication has been started, a physical exam should be checked often (cf. physical signs) for the response to treatment, and it is quite helpful to measure or estimate cardiac output on a relatively frequent basis to aid in this assessment.

The use of vasodilating agents in order to reduce afterload on the myocardium has become an important part of therapy for low cardiac output [41]. Generally, these drugs are helpful to supplement other therapy and may not be useful until blood pressure has been restored toward normal range. These agents may assist in afterload reduction by diminishing ventricular volume (therefore reducing wall ten-
lesions, understanding preparations related to surgery. The choice of medication is somewhat dictated by the respective filling pressures and systemic arterial pressure or vascular resistance. Again, it is often desirable to begin with drugs which can be titrated easily and are rapidly metabolized. Thus, nitroprusside, which has both arteriolar and venodilator actions, or an alpha antagonist, such as phentolamine, may be used first. There are numerous agents with both actions that have a longer duration of action and these may be chosen once the patient is stabilized. As with the other pharmacologic agents mentioned previously, if the response to therapy is insufficient, as determined by changes in perfusion, cardiac output, and measurements of peripheral vascular resistance, then one may want to increase the drug dose or change or add medications. In the interim, it is absolutely essential to examine the patient and review data frequently.

SUMMARY

This review has been intended to provide a general discussion of the factors and principles to be considered when caring for the child who has undergone cardiac surgery. Little attempt has been made to focus on problems unique to a specific type of cardiac disease or certain operative approaches (see [42] for specific recommendations related to each type of cardiac disease). Rather, it is the contention that an understanding of general principles of care, an appreciation for the common problems, and a belief in the need for meticulous attention to detail will provide adequate preparation for those responsible for the care of the child.

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