Mechanical Circulatory Assistance

Current Status and Experience with Combining Circulatory Assistance, Emergency Coronary Angiography, and Acute Myocardial Revascularization

By Charles A. Sanders, M.D., Mortimer J. Buckley, M.D., Robert C. Leinbach, M.D., Eldred D. Mundth, M.D., and W. Gerald Austen, M.D.

Each year more than 600,000 people in this country die from coronary artery disease. It has been estimated that more than half of this number could be saved and returned to a productive life through the prompt application of either temporary or permanent forms of mechanical circulatory assistance (MCA). Such a projection presumes that a means to detect life-threatening events can be devised and that effective devices to support the circulation can be fabricated. In the former instance, identification and delivery of patients at risk to treatment centers must await the development of a comprehensive health care system based on public education, triage centers, and sophisticated technology capable of predicting or detecting potentially serious cardiac events.

By contrast, the methodology to support the failing circulation on a temporary basis is already a reality and has been since the cardiopulmonary-bypass machine was first used successfully for open-heart surgery in 1953. However, because of extensive blood-element destruction accompanying prolonged use, cardiopulmonary bypass has been limited to a time frame exceeding no more than a few hours. To circumvent this limitation and also to explore new approaches with equal effectiveness and greater applicability, new assist devices have been developed, tested experimentally, and, in some instances, used in man. Some of these devices have been no more than an evolutionary step in the continuing development of MCA and have now been discarded. Others, like the cardiopulmonary-bypass machine, have undergone refinements but have persisted largely unchanged from their original design. All devices at present, however, must be considered only a means for temporary circulatory assistance; as yet no device has been fabricated with the capability of assisting and sustaining the circulation permanently.

This article will attempt to put the rapidly growing and changing field of MCA into some perspective. In particular, the goals of MCA will be described, the physiologic principles employed in its application and indications for its use will be discussed, and the current status of the various methods will be reviewed. Furthermore, our own experience in combining MCA with emergency coronary angiography and myocardial revascularization will be reported.

Physiologic Basis of MCA

The development of the various methods of MCA has been based on three well-known physiologic principles: (1) decreased preload; (2) diminished afterload (decreased aortic impedance); and (3) direct cardiac compression. Both (1) and (2) exert a major portion of their effect by reducing left ventricular...
diastolic volume, thus leading to decrease in developed intramyocardial tension and a diminution in myocardial oxygen consumption (MVO₂). The individual devices classified according to the physiologic principles upon which each is based are shown in table 1. It is to be noted that those devices which diminish afterload usually have the added effect of increasing diastolic arterial (and coronary) perfusion pressure. Other devices are a hybrid, combining both the effects of diminished preload and afterload.

Decreased preload may be accomplished by diversion or shunting of blood away from the left ventricle so that the device operates “in parallel” with the heart, thus making it effective in the presence of ventricular fibrillation or standstill. The standard cardiopulmonary bypass machine is the classical means of decreasing preload, although the same effect may be achieved through shunting blood from left atrium (LA) or left ventricle (LV) to aorta or peripheral artery. With the latter approach the lungs of the patient are used to oxygenate the blood; furthermore, reduction in left-sided filling pressures by the bypass pump may clear preexisting pulmonary edema and thus improve oxygenation of the blood.

Afterload is diminished effectively through counterpulsation. Such an approach requires a working left ventricle, thus acting “in series” with the heart. Based on the principle described initially by Clauss et al., arterial blood is withdrawn during systole, allowing left ventricular ejection against a lowered aortic pressure. Time-tension index declines and MVO₂ falls. Reinfusion of blood during diastole increases arterial and coronary perfusion pressure at a time when coronary flow normally is at its height. A competent aortic valve is necessary to prevent retrograde left ventricular overfilling. Thus counterpulsation has the twofold advantage of diminishing myocardial oxygen consumption and increasing coronary perfusion pressure and, potentially, flow to critically stenosed (pressure-dependent) areas of the coronary circulation. Identical effects on the circulation may be obtained using a nonocclusive intraaortic balloon pump. At the beginning of diastole, balloon inflation increases diastolic arterial pressure and promotes runoff of blood to the periphery and at least theoretically back into the coronary arteries. The balloon is deflated just prior to the onset of the next ventricular systole so that the left ventricle ejects its contents into an aorta relatively emptied of blood by the previous balloon systole; hence left ventricular peak systolic pressure is lowered (fig. 1). Direct cardiac compression needs no explanation, since the approach is identical to that employed by direct cardiac massage.

### Table 1

**Classification of MCA Devices**

<table>
<thead>
<tr>
<th>1. Decreased preload</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Venoarterial pumping (total cardiopulmonary bypass)†</td>
</tr>
<tr>
<td>B. Left atrial-aortic bypass</td>
</tr>
<tr>
<td>(1) Closed transpulmonary cannulation</td>
</tr>
<tr>
<td>(2) DeBakey pump†</td>
</tr>
<tr>
<td>C. Left ventricular-aortic bypass</td>
</tr>
<tr>
<td>(1) Closed transarterial left ventricular cannulation†</td>
</tr>
<tr>
<td>(2) Left ventricle-aortic bypass pump</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Decreased afterload</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Counterpulsation</td>
</tr>
<tr>
<td>(1) Arterioarterial pumping*</td>
</tr>
<tr>
<td>(2) Intraventricular balloon pump*</td>
</tr>
<tr>
<td>(3) External regional pressure variation*</td>
</tr>
<tr>
<td>B. Body acceleration synchronous with heart beat (BASH)*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Direct cardiac compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Anstadt cup*</td>
</tr>
</tbody>
</table>

*Devices currently in clinical use.
†Modified to employ counterpulsation in some systems.

*Devices currently in clinical use.
†Modified to employ counterpulsation in some systems.

### Therapeutic Goals and Indications for Use

The current indications, potential applications, and contraindications of MCA are summarized in table 2. At present the purposes of MCA are determined by the clinical situation to which it is applied. Thus far, MCA has been used almost exclusively in patients with cardiogenic shock following acute myocardial infarction (CMI) or cardiac surgery, usually after all other forms of...
therapy including high doses of catecholamines have failed. In such circumstances, the goals of MCA are threefold: (1) to sustain systemic blood flow and oxygen delivery at a level consistent with maintaining normal organ function; (2) to decrease left ventricular work, thus reducing myocardial oxygen consumption and bringing myocardial oxidative demands into better balance with a coronary blood flow limited by intrinsic vascular obstruction, decreased perfusion pressure, or a combination of the two; and (3) to improve myocardial contractility by increasing coronary perfusion pressure and blood flow to ischemic, pressure-dependent areas of myocardium.

Since all assist devices currently available may be used only temporarily, these goals are predicated on the premise that (1) MCA will sustain the circulation until a more definitive procedure, e.g., myocardial revascularization, can be performed, or (2) MCA will reverse myocardial injury by increasing collateral circulation to marginally perfused areas, and return the left ventricle to a level of function sufficient to support the circulation. The evidence accumulated to date strongly suggests that if the latter approach is to be successful, MCA must be applied early in the course of the shock syndrome. The postmortem studies of Page, Caulfield, and their colleagues have indicated that CS-MI is associated with destruction of at least 40% of the LV muscle mass. However, these investigators noted concentric rings of necrosis of varying ages around the original infarct, suggesting that the infarct grew with the passage of time. Furthermore, focal areas of myocardial necrosis were found remote from the site of the original myocardial infarct which were reminiscent of the lesions seen in the hearts of experimental animals treated with toxic and unphysiologic doses of catecholamines. These findings lead to the hypothesis that cardiogenic shock was a self-perpetuating vicious circle (fig. 2). If interdicted early in its course by a therapy such as MCA which decreases myocardial oxidative demands and potentially augments myocardial oxygen delivery, the shock syndrome

![Image](http://circ.ahajournals.org/)

**Figure 1**

*Effect of counterpulsation on LV (top) and aortic (bottom) pressures. Solid line is control pressure. With counterpulsation (dotted line) systolic pressure falls in both while diastolic pressure increases in the aorta.*

<table>
<thead>
<tr>
<th>Contraindications for MCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Irreversible brain damage</td>
</tr>
<tr>
<td>2. Chronic end-stage heart disease (e.g., myocardiopathy)</td>
</tr>
<tr>
<td>3. Severe associated disease</td>
</tr>
<tr>
<td>4. Incompetent aortic valve</td>
</tr>
</tbody>
</table>

*Table 2

Indications and Contraindications for MCA*

<table>
<thead>
<tr>
<th>Indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
</tr>
<tr>
<td>1. Cardiogenic shock secondary to:</td>
</tr>
<tr>
<td>A. Acute myocardial infarction</td>
</tr>
<tr>
<td>B. Myocardial depression following cardiac surgery</td>
</tr>
<tr>
<td>2. Acute heart failure refractory to medical therapy</td>
</tr>
<tr>
<td>3. Recurrent life-threatening ventricular arrhythmias unresponsive to pharmacologic agents</td>
</tr>
<tr>
<td>4. Severe three-vessel chronic coronary disease</td>
</tr>
<tr>
<td>Potential</td>
</tr>
<tr>
<td>1. Circulatory support of patients prior to total cardiac replacement</td>
</tr>
<tr>
<td>2. Anginal syndromes (unstable, &quot;preinfarction&quot;)</td>
</tr>
<tr>
<td>(promotes collateral blood flow)</td>
</tr>
<tr>
<td>3. Acute myocardial infarction (? reduces infarct size)</td>
</tr>
</tbody>
</table>

*Indications*

*Circulation, Volume XLV, June 1972*
could be reversed and its near-100% mortality following acute myocardial infarction perhaps could be reduced. The favorable clinical results obtained by Kantrowitz et al. by early treatment of CS-MI with the intracoronary balloon pump (IABP) provides strong evidence this may indeed be the case.\textsuperscript{15}

There is also experimental and limited clinical evidence to suggest MCA may be useful in treating acute heart failure\textsuperscript{35} and serious ventricular arrhythmias.\textsuperscript{21, 36} Buckley et al. in a notable case found IABP an effective means of controlling recurrent ventricular tachycardia and fibrillation.\textsuperscript{21} With the development of satisfactory artificial hearts and solution of the rejection phenomenon in cardiac transplantation, MCA will be useful also in sustaining patients until total cardiac replacement can be carried out. In our experience IABP has been employed for up to 15 days without serious side effects, thus providing a satisfactory time frame in which to carry out a more definitive procedure.

MCA may be applicable to other, less dramatic clinical situations, particularly if the method is relatively noninvasive, simply applied, and regulated with ease and safety. Sugg et al. have found that MCA in the form of counterpulsation has the important effect of reducing infarct size in the experimental animals.\textsuperscript{37} In dogs whose circumflex coronary artery had been ligated, the amount of left ventricle infarcted was reduced from 28% in the control group to 15% in the group treated with MCA. These results are supported by the studies of Maroko et al. in experimental animals who found that IABP decreased the current of injury around the margin of myocardial infarcts.\textsuperscript{38} These findings suggested that IABP either improved collateral blood flow to the periinfarct region or decreased myocardial work and M\textsubscript{V\textsuperscript{O}}\textsubscript{2} in the ischemic area so that available coronary flow was adequate for myocardial oxidative demands. Reversal of myocardial ischemic changes with arterioarterial pumping was also found by Nishimura et al.\textsuperscript{39} If such findings are transferable to man, the greatest application of MCA may ultimately be in its ability to limit the size of a myocardial infarct. Otherwise, such areas would ultimately progress to infarction in the absence of successful development of collateral circulation. Dolan and co-workers however, using a somewhat similar experimental format, failed to note any increase in perfusion at the periphery of infarction during counterpulsation.\textsuperscript{40}

Measurements of coronary blood flow (CBF) in experimental and clinical studies have also yielded conflicting results. Several animal studies have shown increments in CBF ranging as high as 50% with counterpulsation,\textsuperscript{39, 41} but these findings have not been confirmed by others.\textsuperscript{42-44} In all studies, however, MCA reduced LV work and M\textsubscript{V\textsuperscript{O}}\textsubscript{2}. Clinical observations have been limited. Leinbach et al. found IABP had a variable effect on CBF (measured by the \textsuperscript{129}I-antipyrine technic) and M\textsubscript{V\textsuperscript{O}}\textsubscript{2}; both declined in seven patients, were unchanged in two, and increased in the remaining patient whose systolic arterial pressure (52/35) rose with IABP.\textsuperscript{45} All their observations were made several hours after IABP had been instituted and the condition of nine of the 10 patients had stabilized. These somewhat surprising results were explained by: (1) the performance of the study at a time when mean arterial pressure was well maintained with or without IABP; normal areas of the coronary circulation were not pressure-dependent and capable of autoregulating their flow to lower levels when myocardial oxidative demand in
the myocardium supplied by these vessels decreased by IABP; (2) the inability of the antipyrine method to detect changes in regional myocardial blood flow; significant increments in CBF could well have occurred with IABP in obstructed parts of the coronary circulation since perfusion pressure proximal to such stenoses would result in a variable amount of increased flow distally depending upon the severity of the obstruction. Recently, Mueller et al. have found an average increase in coronary flow of 23 ml/100 g/min in 10 patients treated with IABP. M\(\text{VO}_2\) was essentially unchanged.\(^{32}\) These authors also found a close relationship between aortic pressure and coronary flow; most of their control measurements were performed at mean arterial pressures of 60 mm Hg or less while those with IABP were, with one exception, taken above 60 mm Hg. Powell and co-workers found that IABP had no effect on coronary flow but decreased M\(\text{VO}_2\) slightly in the normotensive animals.\(^{46}\) By contrast IABP in hypotensive animals produced significant increments in coronary flow and M\(\text{VO}_2\) leading these authors to conclude the influence of IABP on the coronary circulation was determined by the coronary perfusion pressure prior to institution of IABP. By applying the data of Powell and co-workers, many of the conflicting results in this area may be explained.\(^{46}\) Further understanding of the influence of MCA on coronary flow and metabolism must await development of satisfactory clinical methods to measure total coronary flow and, perhaps, more importantly, the distribution of such flow.

**Monitoring Facilities**

Currently the application of MCA to patients must be considered to be a complex and often investigative procedure requiring comprehensive monitoring of the clinical, hemodynamic, pulmonary, hematologic, and metabolic status of the patient. Although there may be some variation among groups in the field as to the number of parameters measured, all investigators probably would agree that those listed in table 3 represent data essential to evaluating the performance of a device in the clinical treatment of a patient. In particular the effect of MCA on LV filling pressure is critical in this assessment since this measurement correlates closely with the influence of the device in left ventricular work and M\(\text{VO}_2\).

For example, improper timing of counterpulsation can lead to premature closure or delayed opening of the aortic valve, either of which will hinder left ventricular ejection and result in a higher LV diastolic pressure and increased LV work. Through frequent monitoring of arterial and LV pressure, such a situation can be diagnosed promptly and corrected. Unfortunately, direct measurement of LV pressure can be carried out only for limited periods of time due to the hazard of systemic emboli and local arterial complications from retrograde left heart catheterization. At present LV pressure measurement has been supplanted by the pulmonary artery wedge pressure (PCW), an indirect but accurate reflection of LV filling pressure (fig. 3) in the absence of mitral valve disease. This measurement may be obtained with ease and relative safety by utilizing the Swan-Ganz flow-directed catheter.\(^{47}\) However, caution must be exercised in the use of such catheters to prevent wedging for long periods of time.

---

<table>
<thead>
<tr>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ECG</td>
</tr>
<tr>
<td>2. Systemic arterial pressure</td>
</tr>
<tr>
<td>3. Pulmonary arterial pressure</td>
</tr>
<tr>
<td>4. Urine flow</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intermittent*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pulmonary wedge pressure</td>
</tr>
<tr>
<td>2. Central venous pressure</td>
</tr>
<tr>
<td>3. Arterial (\text{pO}_2), (\text{pCO}_2), pH</td>
</tr>
<tr>
<td>4. Cardiac output</td>
</tr>
<tr>
<td>5. Chest film</td>
</tr>
<tr>
<td>6. Rectal temperature</td>
</tr>
<tr>
<td>7. Hematocrit, white count, platelets, plasma Hb</td>
</tr>
<tr>
<td>8. Clotting tests</td>
</tr>
<tr>
<td>9. BUN, creatinine</td>
</tr>
</tbody>
</table>

*Frequency dictated by clinical situation and speed with which a given measurement is subject to change.

---

Circulation, Volume XLV, June 1972
with resultant pulmonary infarction. Thus, nursing and technical, as well as physician personnel must be trained in maintenance of arterial and venous cannulae, acquisition and analysis of pressure wave forms, cardiac output, and the factors contributing to changes in these and other parameters listed in table 3. In essence then, the facility in which MCA is performed should be dedicated to that purpose as needed, staffed by highly trained personnel on a round-the-clock basis, and equipped with a comprehensive analog-recording system and X-ray equipment. The latter should be available to insert and periodically to verify placement of monitoring catheters. Facilities should also be available to carry out selective coronary and left ventricular angiography if such studies are deemed necessary (see below).

Specific Devices

Bypass Pumps

Total Cardiopulmonary Bypass

This device uses the same pump employed in open-heart surgery. The only exception is that the inferior vena cava is cannulated through the femoral vein and is the only source of venous return. Venous blood is passed through an oxygenator and returned through a femoral artery usually by a DeBakey roller pump. Thus, it is effective even in the absence of any cardiopulmonary function.

Several investigators have employed total cardiopulmonary bypass in the treatment of cardiogenic shock.3, 48, 49 Stuckey et al. in 1957 were the first to report their experience in three patients with myocardial infarction, one of whom was a long-term survivor. Joseph and Maloney49 and, more recently, Kennedy and Bricker3 have extended this experience to a larger group of patients in cardiogenic shock due to a variety of causes. In particular, 22 of 33 patients treated by Kennedy with this technic showed either marked improvement or recovery. The greatest salvage, as might be expected, was among those patients with myocardial depression following cardiac surgery or those in whom cardiac surgery was performed subsequently to correct a life-threatening valvular lesion. Only five patients with acute myocardial infarction and cardiogenic shock were included in this series; one was a long-term survivor. Two of these patients died during bypass; the remaining two, while improved by bypass, subsequently died from a second MI and acute pulmonary embolism, respectively.

Although these results are promising and the widespread availability of heart-lung machines throughout the country makes this approach potentially applicable to large numbers of patients, there are a number of limitations to this technic. First, the time over which cardiopulmonary bypass may be carried out safely is limited to about 4 hours by the blood-element destruction induced by standard oxygenators.2 Thus the shock state must be readily reversible; if not, another less traumatic form of circulatory support must be instituted in place of the cardiopulmonary bypass. Alternatively, acute myocardial revascularization may be effective in improving the shock state and weaning the patient from bypass. Such a procedure necessarily would have to be performed within a remarkably short period of time after beginning bypass to avoid extensive blood-element destruction and the serious side effects attendant upon it. Second, the arterial flow delivered by the standard roller pump is constant and essentially nonpulsatile. This has been shown to

Figure 3

Simultaneous pulmonary artery and LV pressures (left), pulmonary wedge and LV pressures (center), and pullback tracing from LV to aorta (right) in patient receiving counterpulsation (aortic balloon pump). Note close correlation between LV diastolic and wedge pressures.

Circulation, Volume XLV, June 1972
be potentially deleterious to organ function if carried out for more than a few hours.\textsuperscript{50, 51} Arterial pressure is raised throughout both systole and diastole, which requires an increase in left ventricular pressure development and variable increments in LV work and myocardial oxygen consumption, thus diminishing the effectiveness of the bypass in "resting" the heart.

A number of developments have occurred recently aimed at overcoming these problems. Goldman et al. have described a method for pulsatile venaarterial bypass employing a SIMAS counterpulsation device combined with an oxygenator-heat exchanger, thereby diminishing both preload and afterload\textsuperscript{11} and possibly increasing coronary blood flow. Landé et al.,\textsuperscript{52} Bramson and co-workers,\textsuperscript{53} and Kolobow et al.\textsuperscript{54} have reported promising results with new, relatively atraumatic membrane oxygenators which have extended the time frame for their use in experimental animals up to 7 days. At this time, however, all of these approaches are in the experimental stage and, at most, have had limited clinical trials with no long-term survivors.

\textit{Left Atrial-Arterial Bypass}

\textit{Closed-chest transseptal left atrial cannulation} with reinfusion of blood into a femoral artery was initially described by Semming and Dennis in 1962.\textsuperscript{7} A cannula is introduced into the right jugular vein and passed into the right atrium and across the interatrial septum with the aid of a trochar. Blood is drained from the left atrium and reinfused by a roller pump into a femoral artery. This method has the definite advantage of using the lungs of the patient to oxygenate the blood and serving to enhance their function by diminishing left atrial pressure and pulmonary vascular congestion. The technic has been applied to only a few patients without any long-term success. Although no complications have been reported, blood-element destruction accompanying long-term use, the skill required to place the atrial cannula, and the potential hazard of perforating the free wall of the heart during passage of the cannula with cardiac tamponade have limited its widespread acceptance as a clinical method.

The \textit{DeBakey bypass pump} was the first in situ device to be used clinically.\textsuperscript{12} Consisting of an exteriorized, hemispheric, gas-powered chamber with two valves to maintain unidirectional flow, it was placed between the left atrium and aorta in a patient unable to come off cardiopulmonary bypass after open-heart surgery. Later the device and technic were modified to infuse blood into an axillary artery during diastole, thus combining the advantages of bypass with those of counterpulsation. Utilization of the axillary artery allowed the pump to be removed without a second thoracotomy simply by severing the arterial and atrial connections below the skin and oversewing them. The clinical results in two patients with myocardial depression following open-heart surgery were encouraging.\textsuperscript{27} However, the need for a major thoracotomy, blood-element destruction with prolonged use, and prohibitive cost have kept this device from broad clinical application. Nonetheless, the stimulus it has given to other developments makes this device an important evolutionary step in the field of MCA.

\textit{Left Ventricular-Arterial Bypass Pumps}

\textit{Transarterial closed-chest left ventricular bypass} is a technic developed by Zwart et al. requiring retrograde cannulation of the left ventricle from the right subclavian artery with a large-bore catheter.\textsuperscript{24} Blood is withdrawn from the ventricle into a reservoir and initially was reinfused into a femoral artery with a roller pump. More recently a synchronous pulsatile pump has been added to infuse blood only during diastole. Data obtained in experimental animals showed the circulation could be maintained adequately even in the presence of ventricular fibrillation (maximum output 6.2 liters/min) for periods up to 14 hours. Cardiogenic shock could be reversed effectively in the dog, often with complete recovery of the animal. No significant problem was encountered with blood-element destruction. Only two clinical trials have been reported; both were only temporarily successful although neither utilized the synchronized

\textit{Circulation, Volume XLV, June 1972}
version of the system. In both cases there was improvement in arterial blood pressure, a fall in central venous pressure, an increase in urine flow, and a generalized improvement in skin perfusion and mental status. Cardiac output ranged from 2.2 to 5.8 liters in the only case in which it was measured. Pumping duration was 11 and 5% hours, respectively. No plasma-hemoglobin values were reported. Both patients died with massive gastrointestinal hemorrhage, which did not appear to be related to the bypass procedure itself. It was of interest that circulation in the right arm did not seem impaired by the cannula in the subclavian artery.

Shuhmann, Geddes, and Hoff have reported experience in animals utilizing a similar device.55 Their results were quite similar to those of Zwart with the exception that plasma hemoglobin rose markedly after only a few hours of bypass.

Left ventricular-aortic bypass pump is a totally implantable system whose development has been sponsored by the Artificial Heart Program of the National Heart and Lung Institute with the aim of developing a permanent implantable system.10 The pump is connected to the left ventricle and descending aorta and unidirectional flow from ventricle to aorta maintained by a series of valves. It is gas powered and driven by a sophisticated external control system. Experience thus far has been limited to animals. Results have been promising.26 Long-term bypass in 21 calves at flow rates of 4.5–12.0 liters/min was carried out from 7 to 150 days without significant blood-element destruction or thromboembolic problems. Parameters reflecting left ventricular function were generally improved by the bypass pump. However, infection and failure of some components of the support system occurred in almost half the animals. Currently the device is being subjected to a long series of rigorously controlled studies which will preclude clinical use until well into the future.

Counterpulsation Devices

MCA employing a form of counterpulsation was applied first in dogs by Kantowitz and McKinnon in 1958.57 These investigators wrapped the left hemidiaphragm about the descending thoracic aorta and caused it to contract during diastole by triggering stimulation of its phrenic nerve at the end of the T wave in the electrocardiogram. In 1961, Clauss et al. proposed the principle of counterpulsation and developed a device for arterioarterial pumping through a cannula placed in a femoral artery.4 Since then, a number of systems for counterpulsation have been devised, including compressive devices placed around the ascending and descending thoracic aorta (periaortic assist),28, 59 a mechanical auxiliary ventricle,9 the intraaortic balloon-pump system,3, 15, 21, 31 external regional pressure variation,10, 25 and most recently the dynamic aortic patch which is designed to be implanted permanently.20

Although most of these devices have undergone extensive laboratory testing, only a few have proved sufficiently reliable, effective, and safe to be applied to man. The first among these was the auxiliary ventricle. This device was used in only two patients, both with end-stage heart disease. Although neither was a long-term survivor, the device effectively augmented arterial pressure in diastole, reduced systolic arterial and left atrial pressure, and increased cardiac output. However, clotting within the device, blood-element destruction with bleeding, the major thoracotomy required to insert it, and the availability of less traumatic devices with similar hemodynamic effectiveness have limited its further application. Currently there are three types of counterpulsation devices in extensive clinical use: (1) the arterioarterial pump; (2) the intraaortic balloon pump; and (3) systems for external regional pressure variation.

Arterioarterial Pump

Arterioarterial pump requires cannulation of both femoral arteries (SIMAS pump)8 or a subclavian artery (Hauser pump).60 In the latter, the cannula is passed to a point 3 cm above the aortic valve, thus theoretically producing more effective augmentation of diastolic pressure in the aortic root. Both systems are synchronized with the ECG such
that active withdrawal of blood is carried out during ventricular systole and reinfusion of blood is begun at aortic valve closure and continued throughout diastole. Watkins and Callaghan found the effect of the SIMAS device on arterial systolic pressure a useful means for synchronizing the device.\textsuperscript{9} For a given amount of blood pumped, a "null point" could be demonstrated at which systolic arterial pressure was lowered maximally. On either side of this point systolic pressure rose, suggesting that timing of the device has to be adjusted in the individual patient to achieve the greatest reduction in left ventricular systolic pressure.

Experimental studies employing these methods to treat animals in cardiogenic shock induced by coronary artery ligation have shown reversal of the shock state as reflected by an increase in cardiac output and arterial pressure and a fall in left atrial pressure following a 1-hour period of counterpulsation.\textsuperscript{91} Although 80% of control animals died within a month, 80% of treated animals lived for 30 days, and 60% were long-term survivors. Clinical trials have also been promising. Effective support of the circulation was achieved by Watkins and Callaghan,\textsuperscript{8} on a short-term basis in three patients, two of whom had CS-MI. Arterial blood pressure rose to satisfactory levels with counterpulsation, and all patients were weaned from assistance after a maximum of 6 hours of pumping. No measurements of venous pressure, cardiac output, or urine flow were reported, nor was the eventual outcome of the patients commented upon. Rosensweig and co-workers have also employed the SIMAS pump in treating nine patients with CS-MI.\textsuperscript{22} Maximum duration of pumping was 2 hours. Three patients in ventricular asystole or fibrillation could not be supported effectively. In the remaining six, arterial pressures usually rose with assistance, but details of changes in hemodynamic, renal, and cerebral function are not reported. Four patients, all of whom were treated early in their shock state, survived and returned to their previous work. A large clinical experience with the Hauser pump has been reported recently by Jacobey.\textsuperscript{62} Three of nine patients with CS-MI showed steady improvement in arterial pressure, an increase in systemic arterial oxygenation saturation, and a fall in systemic arteriovenous oxygen difference after periods of counterpulsation ranging from 2% to 5% hours. Two of these patients subsequently died within 4 weeks, from progression of their disease; the remaining patient at the time of the report was alive and well after 16 months. Jacobey also has used counterpulsation for a period of 2 hours to treat 14 patients with severe angina pectoris secondary to three-vessel coronary disease. Nine of 13 patients available for evaluation (one patient died of a cerebrovascular accident) were improved symptomatically as judged by a decrease in frequency of pain and improvement in treadmill exercise tolerance. Eight of 11 patients studied with coronary arteriography had findings to suggest more coronary artery vessels were filling after counterpulsation than before.

These results, while encouraging, must be considered in association with the limitations of the method. First, the period over which counterpulsation may be applied is relatively short due to the blood-element destruction resulting from the high shear rates in the pump and cannulae. Clotting in the pump itself occurs after several hours despite systemic heparinization. A patent peripheral arterial system is a prerequisite for application, and local complications from arterial cannulation are a definite hazard.

**Intraaortic Balloon Pump (IABP)**

This approach, described initially by Moulopoulos and co-workers in 1962, employs a nonocclusive catheter-balloon system placed retrograde through a femoral artery into the descending thoracic aorta just distal to the left subclavian artery.\textsuperscript{3} Phasing of the device is accomplished by an external console utilizing the ECG to trigger inflation of the balloon during ventricular diastole and deflation during ventricular systole. Although carbon dioxide was used to inflate the original balloon, this has been replaced by helium because its low viscosity allows extremely rapid movement of gas in and out of the balloon.
The theoretical basis of the intraaortic balloon has been analyzed by Laird and associates. Briefly, these investigators pointed out that the original single-segment balloon tends to inflate at the ends first, with the middle inflating last. If the balloon were occlusive, blood would be trapped between the ends, and its pumping effectiveness impaired. Also, persistent contact with the aortic wall in these circumstances could lead to intimal damage or more serious sequelae. For these reasons, these investigators have developed a balloon with three compartments which will inflate in the middle first and then at the ends simply by making the hole in the middle compartment larger than the end holes.

Of all the types of MCA employed clinically, IABP has received the most extensive use. Kantrowitz and his associates were the first to apply the single-segment polyurethane balloon in the treatment of patients with CS-MI. In their recent report on 30 patients so treated, IABP reversed the shock syndrome in 25. Although hemodynamic and metabolic effects of IABP were not detailed, IABP apparently improved signs of peripheral perfusion, increased urine output, diminished pulmonary vascular congestion, and controlled metabolic acidosis. A survival rate of 45% (nine of 20 patients) was found in patients whose shock developed immediately following myocardial infarction. In contrast, no survival occurred in the 10 patients whose shock was delayed in its onset; thus overall survival was 30%. These findings suggested that the interval between myocardial infarction and onset of shock was critical to survival with IABP. Pumping was continued for as long as 8 days without apparent ill effect. Somewhat surprising was the high incidence of myocardial rupture in this series (seven of 21 patients). Experience with treating a group of 39 patients with CS-MI employing a single balloon with three segments has recently been reported by our group from the Massachusetts General Hospital. The balloon is made of a proprietary product, Aveothane, which compares favorably with blood endothelium in its effect on platelet function. The regulating console, in contrast to that used by Adrian Kantrowitz, has the important design feature of having an isolation chamber which allows use of the same helium repetitively. A sensitive leak-detection and shutoff mechanism greatly minimizes the potential hazard of helium escaping into the circulation in the unlikely event of balloon rupture. As yet perforation or rupture of a balloon has not occurred in extensive experimental or clinical trials. Average duration of shock prior to IABP was 14 hours in 31 patients and 3-9 days in the remainder. IABP reversed the shock state in 31 patients and effected an average increase of 700 ml and 8 mm Hg in cardiac index and arterial pressure, respectively, and a decrease of 4 mm Hg in the pulmonary wedge pressure (fig. 4). The latter was arbitrarily maintained at 18 mm Hg to maximize the effect of the Frank-Starling mechanism. Average arterial pO2 rose from 65 to 127 mm Hg, and signs of pulmonary vascular congestion diminished (table 4). Urine output also increased and the sensorium, if clouded, often cleared. Five of the first 26 patients treated with IABP alone were long-term survivors. This persistently high mortality figure stimulated development of a more aggressive therapeutic policy including coronary angiography and myocardial revascularization in an effort to diminish mortality further (see below). No untoward effects from IABP were encountered even with a period of 15 days of continuous pumping. No instance of myocardial rupture was encountered in the 21 patients coming to autopsy. Goetz and associates have modified the balloon design to include a second small balloon just distal to the main balloon, which occludes the aorta only during diastole. These workers theorize that such a design will maximize diastolic pressure augmentation in the upper half of the body and enhance coronary flow. They cite experimental data in animals to support their claims that this balloon is more effective than a single balloon in improving coronary flow. Nonetheless, clinical data indicating the distal balloon effectively occludes the aorta or actually serves to augment

Circulation, Volume XLV, June 1972
coronary flow beyond that which might be obtained with a single balloon have not been forthcoming. Utilizing their dual-chambered balloon, these investigators were able to reverse the shock state in five cases with CS-MI; one patient was a long-term survivor.\textsuperscript{31} Average hemodynamic changes with IABP included an increment in peak diastolic arterial pressure of 54 mm Hg, a decrease in systolic arterial pressure of 10 mm Hg, and a fall in central venous pressure of 6 mm Hg. Average cardiac index rose from 1 liter/min/m\textsuperscript{2} before assist to 1.4 liters/min/m\textsuperscript{2} immediately after assist. No complications were reported. In another series of 10 patients with CS-MI treated by Mueller and co-workers, IABP (single-segment balloon) effected an average increase in cardiac index of 480 ml, in stroke volume of 7 ml, in diastolic and mean arterial pressure of 51 and 14 mm Hg, respectively, and in systolic ejection rate of 28\%;\textsuperscript{32} by contrast, IABP decreased heart rate by an average of 14 beats/min, systolic pressure by 14 mm Hg, and time-tension index by 310 mm Hg-sec/min. These authors also suggested the major role of IABP might be its ability to stabilize the patient and facilitate more aggressive diagnostic and therapeutic measures.

The advantages of IABP are reflected by the clinical experience cited above. Blood is not handled directly and only minor surgery is required to insert the device. It requires a competent aortic valve and a patent iliofemoral system. Thus it cannot be used in patients with extensive peripheral vascular disease. Dissection of the aorta during introduction of the balloon or with its use are potential hazards. Thromboembolic disease may also

**Table 4**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary artery wedge pressure</td>
<td>18*</td>
<td>22</td>
</tr>
<tr>
<td>(mm Hg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean arterial pressure (mm Hg)</td>
<td>72</td>
<td>64</td>
</tr>
<tr>
<td>Peak systolic arterial pressure</td>
<td>68</td>
<td>78</td>
</tr>
<tr>
<td>(mm Hg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak diastolic arterial pressure</td>
<td>95</td>
<td>55</td>
</tr>
<tr>
<td>(mm Hg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac index</td>
<td>2.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Arterial pO\textsubscript{2} (mm Hg)</td>
<td>127</td>
<td>65</td>
</tr>
</tbody>
</table>

\*Pressures maintained at 18 mm Hg arbitrarily.
MECHANICAL CIRCULATORY ASSISTANCE IN MI

originated about the catheter-balloon system. In one of our own cases, two small emboli were found at autopsy in the kidney and testicle; a second patient who is a long-term survivor has minor claudication in the limb through which the balloon was inserted. Blood-element destruction has not been a serious problem; platelet counts usually drop to about half the normal value with pumping. In our early experience, thrombocytopenia of significant proportions occurred in one case without bleeding and was treated with platelet transfusions. Since employing 10 cc low molecular-weight dextran at hourly intervals, clinically significant depression of the platelet count has not occurred. Uncontrolled bleeding, hemolysis, or plasma-protein degradation has not been encountered.

*Dynamic aortic patch* approach represents an extension of the intraaortic balloon principle. Developed by Sjöransky and co-workers, the device consists of a cigar-shaped flexible bladder made of silicone rubber and lined with Dacron. A conduit is led from the bladder to a control console for synchronizing inflation of the pump in a manner identical to the balloon pump. The bladder is implanted into a longitudinal incision in the descending thoracic aorta such that the inner Dacron surface of the bladder is in direct contact with the aortic lumen. Hemodynamic effects in experimental animals were similar to those obtained with an intraaortic balloon pump of similar size. Considerable problems were encountered with infection, thrombosis, and interruption of pseudointima formation by pumping action of the device. Recently, the device has received its first clinical test in a patient with end-stage heart disease.

**Systems for External Regional Pressure Variation**

*Synchronous regional pressure variation* is a technic in which pressure is varied over the extremities synchronously with the heartbeat. During ventricular systole, the limbs are exposed to a negative pressure of up to −50 mm Hg, thus pulling arterial blood into the extremities, lowering central aortic pressure, and facilitating left ventricular emptying. Negative pressure is converted abruptly to a positive phase exposing the limbs to a maximum positive pressure of 200 mm Hg during diastole. The positive pressure has the combined effect of producing counterpulsation in the arterial circulation and forcing venous blood back to the heart during diastole. Dennis et al. were the first to apply this principle by employing a lower-body sleeve to experimental animals. Soroff and co-workers have extended the technic to man with a device consisting of two large water-filled sleeves placed about the legs and encased in an airtight seal. Pressure variation synchronized with the ECG is accomplished by rapid movement of water in and out of the sleeves. Clinical results in six patients in cardiogenic shock have been encouraging; arterial pressure and urine output rose, color improved, and arterial lactate concentration dropped. In one patient, cardiac output was measured and rose from 1.3 to 1.9 liters/min. With a program of intermittent pumping for as long as 12 hours, two patients could be weaned from assistance although they subsequently expired several weeks later from pneumonia. The remaining four patients died from progression of their underlying disease despite transient circulatory improvement with the device. No harmful effects were encountered with the system, despite the potential hazard of inducing pulmonary embolism by forcing preexisting venous thrombosis out of the legs with the positive pressure phase of pumping. Patients did note, however, local discomfort over the legs with prolonged pumping. Cohen and co-workers have investigated a newer, more portable, sequenced external pulsation system consisting of sleeves placed on all four extremities. Data in experimental animals have suggested that the system may be an effective method of supporting the failing circulation. No clinical trials have been reported to date.

External regional pressure variation is an appealing although relatively untested approach to circulatory support because of its noninvasive character, safety, and potential application to large groups of patients.
Body Acceleration Synchronous with Heartbeat (BASH)

This system, appropriately named, consists of a horizontal table capable of moving rapidly at forces up to 1.5 g, thus displacing the inert column of blood in the aorta. If properly phased with ventricular systole, such movement of blood could facilitate left ventricular emptying. Initially described by Arntzenius, the BASH table was designed to move caudad a distance of 2 cm at a force of 1.5 g and assist in moving blood out of the left ventricle into the aorta during ventricular systole. It was found, however, that the cephalad displacement of blood in the thoracic and abdominal aorta tended to minimize the desired effects. Recently, the direction of displacement has been changed to cephalad and the length of displacement increased to 15 cm at a force of only 0.25–0.5 g. (Arntzenius AC: Personal communication.) This alteration has a considerably greater effect in reducing left ventricular systolic pressure by pushing the inert column of blood in the thoracic and abdominal aorta into the extremities during systole, and having the natural elastic recoil of the arterial system augment arterial pressure in diastole, thus mimicking counterpulsation. As yet no clinical results have been reported with this technic. It is appealing, however, because of its ease of application and noninvasive character, but its potential to induce harmful side effects remains to be determined.

Direct Cardiac Compression

A variety of devices have been fabricated to compress the heart directly, including pneumomassage, a constricting rubber ventricle, an intraventricular cardiac balloon pump, and the Anstadt cup. Of these, the last device has been evaluated the most extensively in experimental animals and in clinical trials. This form of mechanical ventricular assistance (MVA) consists of a rigid cup lined with an inner silastic sleeve bonded to the apex and rim of the cup. The cup is placed over the heart and positive and negative pressures introduced into the space between the sleeve and the cup, thus producing direct cardiac compression. Gentle suction through a separate channel at the apex of the cup keeps the heart firmly in place. MVA is effective in the presence of ventricular fibrillation or can be synchronized through the ECG to the beating heart. Observations on experimental animals in ventricular fibrillation have shown that arterial pressure and cardiac output can be maintained at well above 50% of control valves in most instances. Clinical trials in 20 patients have included patients with cardiac arrest from primary myocardial disease and myocardial infarction, and a few in whom MVA was applied as a means of preserving donor kidneys. Arterial pressure was restored in most instances to near normal levels, and cardiac output reached as high as 5.2 liters/min. Duration of pumping ranged from 1 to 10 hours. There was only one short-term survivor; the remainder died from the consequences of their primary disease.

The major advantage of this method appears to be its effectiveness in the presence of ventricular fibrillation, the utilization of the vascular system of the patient, and the extended time over which it can be employed. Nonetheless, it requires a major thoracotomy which would appear justified only as a holding action pending complete heart replacement, or excision of donor organs.

Criteria for Discontinuing MCA

Indications for discontinuing MCA fall into three general categories: (1) The time limit beyond which a particular form of MCA results in serious blood-element destruction has been approached or exceeded, or the device has produced a serious, unforeseen complication requiring its discontinuation. (2) The condition of the patient has deteriorated and recovery is impossible. (3) The hemodynamic status of the patient has improved to the point where MCA is no longer required.

Assessment of the contribution of MCA to circulatory support has been based largely on the response of arterial pressure, cardiac output, and the clinical status of patient to diminution or cessation of MCA. If these
parameters deteriorated, MCA was reinstalled and continued for a variable period depending upon the time frame over which it is safe to employ that particular type of MCA. With IABP time is not a consideration, and both Kantrowitz and our own group have evolved a somewhat similar protocol to appraise the influence of MCA in the individual patient. Once IABP is begun, it is continued for several hours without interruption. If the patient improves and stabilizes, IABP is ceased abruptly and the patient is observed for signs of deterioration. If none appears in 30 min, Kantrowitz will resume IABP for another 30 min; if there is no further improvement, IABP will be discontinued, with the balloon left in place for an additional 24 hours and then removed if no longer needed.

In our own experience, we have found comparison of hemodynamic measurements and arterial pO₂ “on” and “off” IABP extremely valuable in assessing the balloon-dependence of a patient. In several studies, cardiac output and arterial pressure were well maintained after stopping balloon pumping despite an abrupt rise in pulmonary wedge pressure (fig. 5) and a fall in arterial pO₂ indicating a deterioration of left ventricular function. We therefore feel these latter two measurements are especially sensitive in evaluating the contribution of IABP to assisting left ventricular function. If deterioration appears with cessation of pumping, IABP is reinstalled for another 6-12 hours and the procedure repeated. If IABP is found to have no effect on the measured variables, the patient is gradually weaned over the subsequent 12-24 hours by only partially inflating the balloon with 5-min periods of full inflation every hour to minimize clot formation. A complete hemodynamic study is repeated 12-24 hours later, and if unchanged or improved the balloon is removed. If significant deterioration has occurred, IABP is reinstalled.

Role of Emergency Coronary Angiography and Myocardial Revascularization

With the continued high mortality (80%) in our first 26 patients treated with IABP alone, it became obvious that MCA would have to be combined with a more definite procedure such as acute myocardial revascularization, myocardial resection, or both, if mortality were to be decreased further. Theoretically, earlier
institution of IABP in the course of the shock state than had been possible in some of our cases might have increased survival somewhat, although this seems unlikely in view of the widespread myocardial necrosis and severity of obstructive coronary disease found in the hearts of patients with CS-MI coming to autopsy. A role in protecting myocardial tissue at risk from the shock state can be invoked logically for IABP through its effect on decreasing MVO₂ and bringing myocardial oxidative demand into balance with available coronary blood flow. Permanent improvement with IABP alone is predicated on recovery of ischemic myocardium through increased flow to that area by opening up new channels for coronary flow or further expansion of preexisting ones.

Upon analyzing the five survivors treated with IABP alone, it appeared that such improvement, if it did occur, would be manifest within 12–24 hours after beginning IABP. Hemodynamic measurements in such patients showed a prompt rise in arterial pressure to a mean above 75 mm Hg (without vasoactive agents), improvement in cardiac index to above 2.0 liters/min/m², and a decline in pulmonary wedge pressure to 18 mm Hg or less. Patients who did not improve to the point where discontinuation of IABP could be considered during this time either could not be weaned from the balloon at a later date or died from progression of their heart disease a few days to 3 weeks following cessation of IABP. Although IABP maintained mean arterial blood pressure at an average of 70 mm Hg, cardiac index was uniformly less than 2 liters/min/m² and pulmonary wedge pressure always above 18 mm Hg. Subsequently, we have evolved the following criteria for emergency coronary angiography in patients treated with IABP: 

1. Failure to show significant hemodynamic improvement within 12–24 hours on a therapeutic program including IABP and catecholamines; 
2. Increasing catecholamine requirements despite IABP; 
3. Marked dependence on IABP after 24 hours; or 
4. Recurrent hemodynamic deterioration in a patient previously weaned from IABP.

Coronary arteriography and left ventriculography in two views (if possible) were carried out utilizing the Sones technic with IABP continuing throughout the study. In the first 20 patients studied with angiography, only one—the first in the series—died in proximity to the angiographic procedure. He expired from an arrhythmia 30 min after completion of the procedure when IABP had to be discontinued for technical reasons during transfer back to the intensive care area. Subsequent patients have done well despite the occurrence of severe myocardial depression during angiography, particularly after the left ventricular angiogram. IABP appears essential to support these patients at this time, since it is our belief that without it the mortality from the diagnostic procedure in itself would be high.

In analyzing the results of angiography, one patient (fig. 6) was considered inoperable. The remaining 18 patients were felt to be operative candidates based on the apparent feasibility of bypassing coronary obstructive disease and retention of some degree of left ventricular contraction. One patient refused operation and a second died immediately prior to surgery from an arrhythmia. Sixteen patients were operated upon. The operative procedure was surprisingly similar in that 12 patients required a bypass graft to the right and left anterior descending coronary arteries; one had a single graft to the right coronary artery, and another a double graft to the anterior descending and circumflex arteries. Two additional patients had infarction resection alone. Seven patients with bypass grafts also had myocardial resection, and three had mitral valve replacements. These measures (often unsuccessful) were taken after bypass grafting was completed to facilitate coming off cardiopulmonary bypass. Fifteen patients required continuing IABP in the immediate postoperative period, but, like patients treated with IABP alone, long-term survivors showed steady improvement in their hemodynamic status and IABP could be stopped within 48–72
Selective coronary angiography performed during balloon pumping. Right coronary artery injection (top, left) shows vessel relatively free of disease; note balloon pump in left of picture and Swan-Ganz catheter at right. Left coronary injection shows occlusion of anterior descending branch at origin; circumflex system is widely patent. Schematic representation of left ventricular angiogram shows no change from diastole (solid line) except for small area of contraction (dotted line) on posterior and inferior surface. Slight paradoxical expansion is present at apex.

In an effort to define criteria in the selection of patients for surgery, the angiograms were reviewed and the findings compared with those found at operation and/or autopsy. The left ventricular angiogram was divided into six segments based on the right and left anterior oblique views: anterior, anterolateral, anteroseptal, apical, posteromedial, posterolateral, and inferior. The presence or absence of contraction in any given segment was related to the evidence of coronary perfusion to that area. Ventricular cavity in systole and diastole was also measured to obtain a rough approximation of ejection fraction. In general, it was found that contraction and perfusion were

hours (fig. 7). Seven patients have been long-term survivors with follow-up of 2–16 months. These include three patients receiving bypass grafts alone, two with bypass grafts and myocardial resection, one patient with bypass grafts and mitral replacement, and one patient with infarctectomy alone. One late death has occurred due to abdominal infection following gastric surgery.74–76

In an effort to define criteria in the selection of patients for surgery, the angiograms were reviewed and the findings compared with
directly related to one another; absence of contraction usually indicated obstructive disease in the corresponding artery. Increasing cavity size usually was associated with increasingly severe abnormalities in perfusion and contraction of all segments; in the single exception to this finding, there was virtually no evidence of contraction as measured by a change in ventricular area. In the seven long-term survivors, there was evidence of some degree of perfusion and contraction in at least four of the six segments (fig. 8). All nonsurvivors showed contraction in no more than three segments, indicating that retention of ventricular contraction, however slight, is an important prognostic factor. The pattern of obstructive coronary disease was remarkably similar; all patients had extensive involvement of the distribution of the left anterior descending artery, indicating that involvement of this vessel is necessary to develop CS-MI. If the anterior descending artery was obstructed at its origin, extensive impairment of ventricular contraction usually occurred involving anterolateral, anteroseptal, and apical segments (fig. 7). The most common combination of lesions was involvement of the right and left anterior descending coronary arteries with the circumflex or circumflex marginal branches providing the major source of blood supply to the myocardium.

Comment

The clinical use of MCA has been restricted largely to patients with severe left ventricular dysfunction following open-heart surgery or myocardial infarction, usually after all other therapy has failed. The results, though limited, have shown clearly that certain of these devices will support the circulation safely and effectively in such patients for a varying period of time. In our own institution, IABP has become standard therapy in patients with CS-MI. It has become clear that IABP alone will probably not salvage more than 20–30% of such patients. When IABP is combined with emergency angiography and acute revascularization, about 40% of patients can be saved. In the majority, however, total cardiac replacement appears necessary because myocardial damage is too extensive to be reversed by any other surgical technic. Other therapeutic roles for MCA are being investigated both clinically and experimentally (table 2), and it is in this group that the greatest application of MCA as a therapeutic tool may ultimately be found.

A number of problems may be identified in appraising the field of MCA at this time. First, further development and clinical testing of new devices is required, since no form of MCA now available is potentially applicable to all clinical situations. Second, the major challenge in developing long-term or permanent MCA is the synthesis and testing of a
durable biomaterial which will not destroy the blood elements or promote clotting. Third, most forms of MCA are invasive. Although in most instances the surgery to insert the device is relatively minor, it is desirable to have a vascular surgeon available. Fourth, the facilities and staff required to serve MCA must be more widely available to serve the general population. At present, critical care units to support such efforts are limited to only a few large hospitals. Fifth, the regulatory consoles for MCA are often complex in their circuitry and operation. Skilled personnel to operate and service such systems are required. Durability and simplicity in such consoles are necessary in order to apply some devices on a broad scale.

Sixth, assessment of the efficacy of a device is hindered by variability in selection of criteria among investigators for evaluating the performance of a device. This problem is compounded further by the instability of the clinical situation to which MCA is often applied and the difficulty in determining whether the device itself is responsible for clinical improvement or deterioration, or in fact has had any effect at all. Furthermore, data on possible side effects of a device are often lacking. Lastly, development of new, preferably noninvasive methods to quantitate and regionalize coronary blood flow, to size myocardial infarcts, and to separate normal, ischemic, and necrotic tissue is necessary in selecting patients for MCA and evaluating its

Figure 8

Selective coronary arteriography in patient with relatively good preservation of ventricular contraction despite extensive but bypassable coronary disease. Diastolic (solid line) cavity size is not markedly enlarged and contraction (dotted line) is present in four of six segments.
influence on coronary blood flow and ventricular contraction.

None of these problems is insoluble, but time, proper funding, ingenuity, and dedication will be required for their solution. As the answers become available, the role of MCA and its impact in cardiovascular disease will become defined.

References


Circulation, Volume XLIV, June 1972


27. DEBakey ME: Left ventricular bypass pump for cardiac assistance. Amer J Cardiol 27: 3, 1971


38. MAROKO PR, WATANABE T, COVELL WR, BRAUNWALD E, BERNSTEIN EF, ROSS J JR: The effect of positive inotropic agents and counterpulsation on myocardial ischemic injury following experimental coronary occlusion. Circulation 42 (suppl III): 1311


42. WILLMAN VL, COOPER T, RIBBERA, HANLON CR: Cardiac assistance by diastolic augmentation: Hemodynamic evaluation in dogs with complete heart block. Trans Amer Soc Artif Intern Organs 7: 198, 1961


67. Time Magazine, August 23, 1971, p 52


Circulation, Volume XLV, June 1972

Mechanical Circulatory Assistance: Current Status and Experience with Combining Circulatory Assistance, Emergency Coronary Angiography, and Acute Myocardial Revascularization

CHARLES A. SANDERS, MORTIMER J. BUCKLEY, ROBERT C. LEINBACH, ELDRED D. MUNDTH and W. GERALD AUSTEN

Circulation. 1972;45:1292-1313
doi: 10.1161/01.CIR.45.6.1292
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1972 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/45/6/1292.citation

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/