

CLINICAL AND EXPERIMENTAL EXPERIENCES ON ASSISTED CIRCULATION WITH SPECIAL REFERENCE TO ITS INDICATIONS AND OPTIMAL FLOW RATE

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ABSTRACT

1) The different modes of assisted or controlled circulation have been considered for an intractable cardiac failure. The authors advocated the following classification that may be useful for the hemodynamic study of assisted circulation.

A) The partial bypass technique:

- (1) veno-arterial pumping,
- (2) right ventricular partial bypass,
- (3) left ventricular partial bypass, and
- (4) partial cardiopulmonary bypass.

B) The total bypass technique:

- (1) right ventricular total bypass,
- (2) left ventricular total bypass,
- (3) synchronized arterial counterpulsation, and
- (4) total cardiopulmonary bypass.

2) Indication for various types of assisted circulation were discussed on the basis of the clinical and experimental experiences.

3) The authors proposed the concept of an optimal flow rate of assisted circulation employing partial bypass technique. The maximum efficacy of assisted circulation may be obtained by perfusing at the optimal flow rate, while the serious complications caused by perfusing at an unnecessarily high flow rate are avoided.

The authors previously reported the efficacy of veno-arterial pumping and partial cardiopulmonary bypass on dogs with experimentally induced cardiac failure and on clinical cases of acute pulmonary edema or intractable congestive cardiac failure, the clinical application of a properly designed pumping device "Circulatory Assistor H-1" in these cases, and the hemodynamic and histological studies on the experimental animals in which prolonged venoarterial pumping was performed.

On the basis of these observations, an attempt is made in this paper to

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elucidate the indications for various types of assisted circulation and also the concept of the optimal flow rate of assisted circulation when the partial bypass technique is employed.

CLASSIFICATION OF ASSISTED CIRCULATION

The following different modes of assisted or controlled circulation have been considered for an intractable cardiac failure.

- (1) veno-arterial pumping,
- (2) selective right ventricular bypass,
- (3) selective left ventricular bypass,
- (4) synchronized arterial counterpulsation, and
- (5) partial or total cardiopulmonary bypass.

The essential criticism for this classification lies in that the ventricle is bypassed, or assisted, by a given type of assisted circulation.

Since available evidence indicates that there is a significant difference between the response of a failing heart to "the partial bypass" and to "the total bypass" during the same mode of assisted circulation, the following classification may be useful for the hemodynamic study of assisted circulation.

A) The partial bypass technique:

- (1) veno-arterial pumping,
- (2) right ventricular partial bypass,
- (3) left ventricular partial bypass, and
- (4) partial cardiopulmonary bypass.

B) The total bypass technique:

- (1) right ventricular total bypass,
- (2) left ventricular total bypass,
- (3) synchronized arterial counterpulsation, and
- (4) total cardiopulmonary bypass.

INDICATIONS FOR VARIOUS TYPES OF ASSISTED CIRCULATION

Generally, assisted circulation should be reserved for cases in which all conservative treatments have been exhausted.

I. Veno-arterial pumping and partial cardiopulmonary bypass

The survival time of dogs with experimentally induced cardiac failure has been uniformly increased by the application of partial cardiopulmonary bypass. Hemodynamic studies in experimental animals, in which venoarterial pumping or partial cardiopulmonary bypass was applied, indicated that the left as well as the right ventricular stroke work was decreased as a result of a decrement in both the volume work and the pressure work.

Furthermore, in ten clinical cases of veno-arterial pumping for cardiac failure (Table 1), the following results were obtained.

TABLE 1. Summary of Clinical Cases, in Which Assisted Circulation (Veno-arterial Pumping) was Applied

Case No.	Patient	Age (yrs) Sex	Body Weight (kg)	Diagnosis	Assisted Circulation		Remarks	
					Flow Rate (cc/min)	Duration (cc/kg/min)(hrs: min)		
1	T. M.	28 M	50	Gastric Cancer, Acute Pulm. Edema	600	(12)	5 : 30	Remarkably Improved
6	S. M.	48 F	45	Breast Cancer, Acute Pulm. Edema	900	(20)	3 : 17	Remarkably Improved
9	H. T.	56 F	55	Pulm. Tubercu- losis, Acute Cor Pulmonale	220	(4)	2 : 00	Cured
10	R. S.	16 M	45	Bronchiectasia, Acute Cor Pulmonale	900	(20)	1 : 10	Unchanged
2	M. S.	38 F	40	Mitral Stenosis, Congestive Failure	1 500	(30)	2 : 10	Remarkably Im- proved there- after. Mitral Commissurotomy Performed
3	T. K.	47 F	40	Comb. Valvul. Disease, Con- gestive Failure	800	(20)	2 : 27	Unchanged
4	T. H.	17 M	40	Ebstein's Dis- ease, Congestive Failure	1 600	(40)	3 : 30	Satisfactorily Im- proved thereafter. Glenn op. Performed
5	K. K.	31 M	50	Mitral Stenoin- suff., Congestive Failure	800	(16)	2 : 18	Unchanged
7		47	1 300		(28)	5 : 01	Satisfactorily Improved	
8	K. W.	31 F	50	Comb. Valvul. Disease, Con- gestive Failure	1 500	(30)	5 : 00	Unchanged

(1) A notable decrease in the pulmonary arterial pressure and the right atrial pressure,

(2) a marked reduction of the cardiac contour and the pulmonary vasculature,

(3) a subjective improvement in the patient's condition, and

(4) in cases of acute pulmonary congestion, a prompt improvement with clearing of signs of pulmonary congestion.

These observations strongly suggest that veno-arterial pumping or partial cardiopulmonary bypass is definitely indicated in cases of acute right ventricular failure and of acute pulmonary congestion caused by mitral lesions as long as the left ventricle remains compensated. They also suggest that these two procedures may be indicated in cases of an intractable chronic congestive failure, in anticipation of an improvement in the patient's condition as a result of interrupting the vicious cycle of this pathological state.

At present, there is a general agreement as to the usefulness of veno-arterial pumping in right ventricular failure, but considerable controversies as

to its effects in left ventricular failure. Our observations, from both experimental studies and clinical experiences, demonstrate that veno-arterial pumping does not necessarily have harmful effects on left ventricular failure. The only possible explanation for this result is as follows: the work for each ventricle is expressed by

$$W = QR + \frac{1}{2} mV^2$$

where Q is the volume of ejected blood, R the mean arterial pressure, m the mass of ejected blood, and V the average velocity of ejected blood.

If the mean arterial pressure was reduced during systole, with the other factors being kept constant, the calculated work have to be decreased.

Through the application of veno-arterial pumping, the mean arterial pressure can be reduced optionally by inducing a hypovolemic condition, without such an untoward reaction as shock. On the other hand, veno-arterial pumping with a non-pulsatile pump induces a decrement in the pulse pressure, that is, a decrease in the systolic pressure and an increase in the diastolic pressure. As a result, it is possible to obtain a condition where the diastolic pressure is elevated slightly above the control level, even under a reduced mean arterial pressure. Thus, a sufficient coronary flow caused by a slightly elevated diastolic pressure and a reduction in the left ventricular stroke work resulting from a decrease in the mean arterial pressure may be provided simultaneously.

An essentially similar deduction can also arrive at in the case of partial cardiopulmonary bypass.

II. Selective right ventricular bypass

Theoretically, this procedure provides the least questionable support to the failing right ventricle. However, the necessity of thoracotomy prior to the cannulation into the pulmonary artery limits the clinical applicability of this procedure. Hemodynamic effects similar to those of the right ventricular partial bypass may be obtained by employing veno-arterial pumping or partial cardiopulmonary bypass.

III. Selective left ventricular bypass and synchronized arterial counterpulsation

The left ventricular myocardial usage of oxygen as well as the left ventricular stroke work can be decreased by the application of these procedures. It is of interest that there is an essential difference in the mechanism of reduction of the left ventricular stroke work between selective left ventricular bypass and synchronized arterial counterpulsation. Selective left ventricular bypass reduces the volume work of the left ventricle, in proportion to the flow rate; on the other hand, synchronized arterial counterpulsation with correct phasing minimizes the pressure work of the left ventricle.

The clinical applicability of left ventricular bypass is generally limited by the necessity of thoracotomy or of a transeptal cannulation through the jugular vein into the left atrium. In synchronized arterial counterpulsation, merely the exposure of the external iliac artery is required as the surgical operation.

At present, the hemodynamic effect of these two procedures on a right ventricular failure remains obscure. Whatever may be the mode of action, a possibility exists that a right ventricular failure may be aggravated by these two procedures.

IV. Total cardiopulmonary bypass.

Theoretically, total cardiopulmonary bypass, which is to be regarded as a controlled circulation rather than an assisted circulation, is the most powerful measure for relieving a bilateral heart failure. However, the duration of the performance of this procedure is clinically limited.

V. Contraindications for assisted circulation.

None of the various modes of assisted circulation are applicable in cases of aortic regurgitation or left-to-right shunt.

On the basis of these discussion, each indication for the various modes of assisted circulation is listed in Table 2.

TABLE 2. Indications for Various Modes of Assisted or Controlled Circulation

Procedure	Right heart failure	Left heart failure	
		Left atrial failure	Left ventricular failure
Veno-arterial pumping	++	+	- or +
Partial cardiopulmonary bypass	++	+	- or +
Selective right ventricular bypass	++	-	-
Selective left ventricular bypass	?	++	++
Synchronized arterial counterpulsation	?	+	++
Total cardiopulmonary bypass	++	++	++

Key: ++ Markedly effective.

+ Satisfactorily effective.

- Ineffective or harmful.

? Providing the questionable support to the failing ventricle (see text).

OPTIMAL FLOW RATE OF ASSISTED CIRCULATION

When veno-arterial pumping or partial cardiopulmonary bypass, under a normovolemic condition, was performed on a healthy dog, the total tissue perfusion remained unchanged. Clinically, on the other hand, by the application of veno-arterial pumping at a flow rate of 16 to 30 ml/kg/min., the patient's cardiac output during this procedure was increased, even under a slightly hypovolemic condition, from 3 430 to 3 620 ml/min. in case #2, from 2 670 to

3 230 ml/min. in case #5, and from 3 190 to 3 430 ml/min. in case #8. As a result, the total tissue perfusion during this procedure was increased from 3 430 to 5 120 ml/min. in case #2, from 2 670 to 4 030 ml/min. in case #5, and from 3 190 to 4 930 ml/min. in case #8.

At the same time, a marked decrease in the right ventricular stroke work, resulted from the reduced pressure work, was obtained. The phenomenon that the output of the ventricle which is bypassed by veno-arterial pumping increases to above the control level is in accord with Starling's law of the heart with myocardial damage. It was notable that the efficacy of this procedure correlated well with the degree of the increase in the total tissue perfusion.

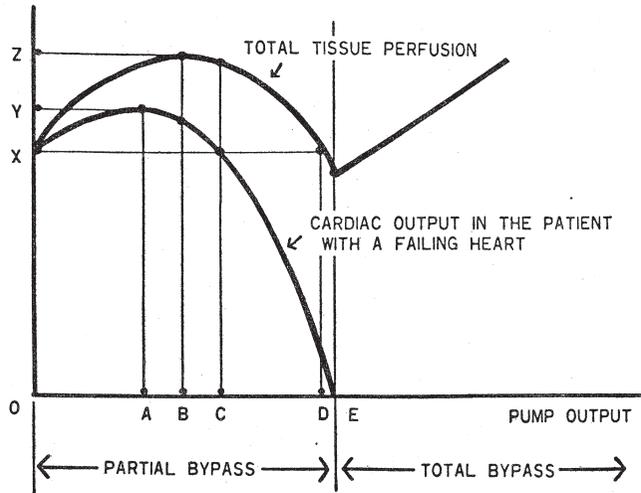


FIG. 1. Diagrammatic representation of the possible interrelationship between the pump output and the patient's cardiac output or total tissue perfusion during an assisted circulation.

- X: the pump output or total tissue perfusion before assisted circulation is applied.
- Y: the maximum cardiac output induced by assisted circulation.
- Z: the maximum total tissue perfusion induced by assisted circulation.
- A: the pump output which induces the maximum cardiac output (Y).
- B: the pump output which induces the maximum total tissue perfusion (Z).
- C: the pump output which induces a marked increment in the total tissue perfusion, the cardiac output remaining unchanged from that of the control level (X).
- D: the pump output which induces a marked decrement in the cardiac output, the total tissue perfusion remaining equal to that of the control level (X).
- E: the pump output which makes the transition from partial bypass to total bypass.

These observations have led to the concept that in assisted circulation, which is performed by adopting a partial bypass technique, an optimal flow rate exists which benefits most the failing heart, and that such a flow rate differs with cases and may vary under different condition in the same case (The maximum efficacy of assisted circulation may be obtained by perfusing at the optimal flow rate, while the serious complications caused by perfusing at an unnecessarily high flow rate are avoided).

The possible interrelationship between the pump output and the patient's cardiac output or total tissue perfusion during an assisted circulation is represented diagrammatically in Figure 1. In this diagram, five critical values of the pump output may be seen. Among these various outputs, the pump output at B induces the maximum total tissue perfusion. It is inferred that the flow rate approximate to the pump output at B indicates the optimal flow rate of assisted circulation while adopting a partial bypass technique.