A COMPARATIVE STUDY ON THE EFFECTIVENESS OF PULSATILE AND NON-PULSATILE BLOOD FLOW IN EXTRACORPOREAL CIRCULATION

by

TAKESHI OGATA, YOSHIKAZU IDA, AKIRA NONOYAMA, JUN TAKEDA and HIDEO SASAKI

From the 2nd Surgical Division, Kyoto University Medical School
(Director: Prof. Dr. YASUMASA AOYAGI)
(Received for publication Sept. 7, 1959.)

It is of prime importance to solve the problem as to whether pulsatile flow should be used for extracorporeal circulation in a similar fashion as in normal circulation, or non-pulsatile flow would be safely available for a certain time period required for open heart surgery without any circulatory derangement. WESOLOWSKI et al.[8] demonstrated in 1955 that arterial pressure, balance of in- and outflow and physiologic function of the whole organism were successfully maintained as long as three hours under extracorporeal circulation by means of non-pulsatile flow. Therefore, almost all the conventional artery pumps have never been deviced so as to generate an efficient pulsatile flow as seen in normal circulation.

Many problems are still unsolved in pathologic physiology of the organism subjected to extracorporeal circulation, and various unfavorable phenomena have frequently been encountered in the clinical application of heart-lung machine, such as unexpected fall in blood pressure, unbalanced in- and outflow, development of metabolic acidosis etc.,[1)~5)] the causes of which are not yet clarified. It has been suggested by us that the diminution or disappearance of pulsation in arterial blood flow during extracorporeal circulation may play a significant role in the possible causes. In order to assure the above suggestion, a series of experiment was conducted at our laboratory as described in the following chapters.

METHODS AND MATERIALS

The artery pump used for this experiment was first constructed in our laboratory under the directon of Dr. KAMIMOTO, Professor of the Faculty of Technology, Kyoto University. Its schematic diagram is illustrated in (Fig. 1). The output and the pulse frequency of this pump can be adjusted from 0 to 50 cc. per stroke and from 40 to 140 strokes per minute, respectively. The main advantages of the pump are that its pressure curve closely resembles that of the living organism (Fig. 2), and that it causes minimal damage to the blood cells (Fig. 3). For aeration of blood a foam oxygenator of Waud-type was employed. The animals used were adult mongrel dogs weighing 8 to 12 kg. For arterial delivery a metal cannula of 3 mm. caliber was inserted through the left carotid artery into the aorta, and for venous cannulation, two vinyl tubes of 5 mm. caliber were passed through the right atrium

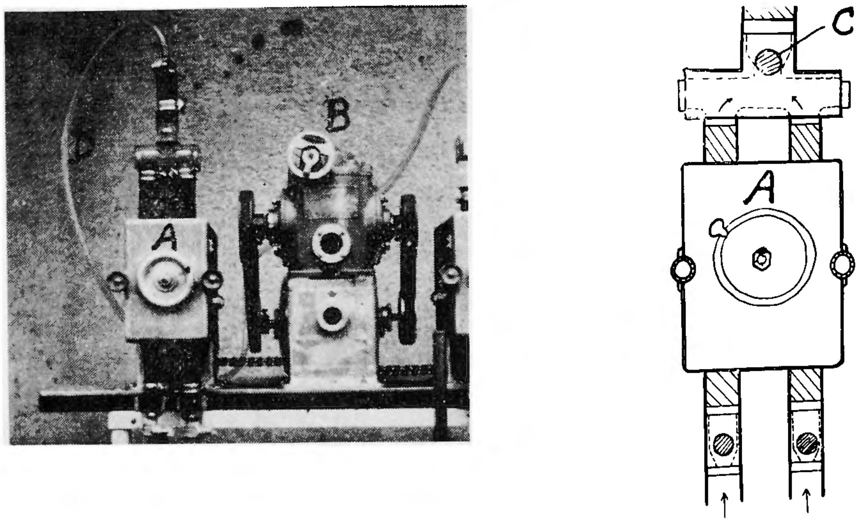

Fig. 1 Close up photograph and schematic diagram of the arterial pump.
A. Control section of the stroke volume.
B. Cotnrol section of the stroke frequency.
C. Stainless steel ball valve.
D. Arterial output to animal.

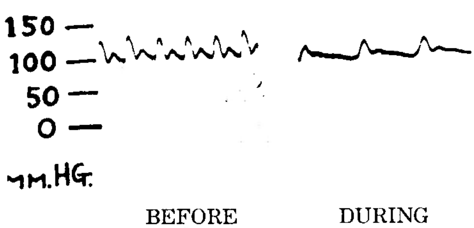

Fig. 2 Electromanometric pulse-wave traces taken within the femoral artery. the "During" trace was recorded during a experiment using a pulsatile flow.

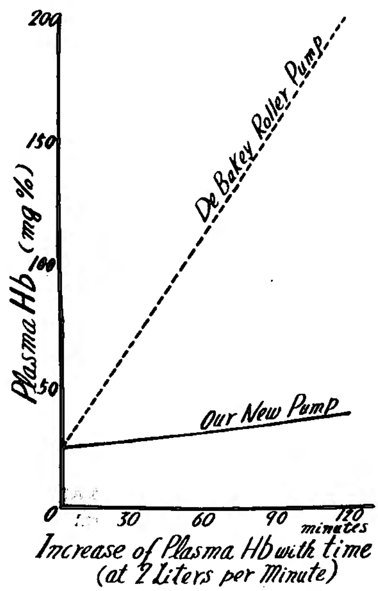

Fig. 3

and one was placed into the superior and the other into the inferior vena cava. Venous blood was sucked by gravity at a negative pressure of about 30 cm. H_2O and was collected in the reservoir. Arterial and venous blood samples, drawn simultaneously during perfusion, were analyzed by the Van Slyke technique for oxygen content, oxygen capacity and carbon dioxide content. Oxygen consumption was calculated from the arterial-venous oxygen difference and rate of flow. The pH was measured by the Shimadzu model pH meter with a constant temperature water bath at 37°C. and the buffer base was calculated from the Singer-Hasting's nomograms. The arterial pressure was recorded from the femoral artery, the venous pressure from the inferior vena cava.

Throughout the experiment the pulse rate was set at 70 per minute, and when a non-pulsatile flow was required pulsation was removed by an air chamber interposed in the delivery tube and at the same time cardiac arrest was induced by electric shock. The flow rate was accurately determined with the electromagnetic flowmeter. Care was taken to keep the rectal temperature above 35°C. during the procedure.

The animals were divided into two groups, i. e. the pulsatile and non-pulsatile, and observations were made on each group with either pulsatile or non-pulsatile flow under the same flow rate for a period of sixty to ninety minutes of extracorporeal circulation.

RESULTS

1) Arterial blood pressure (Fig. 4)

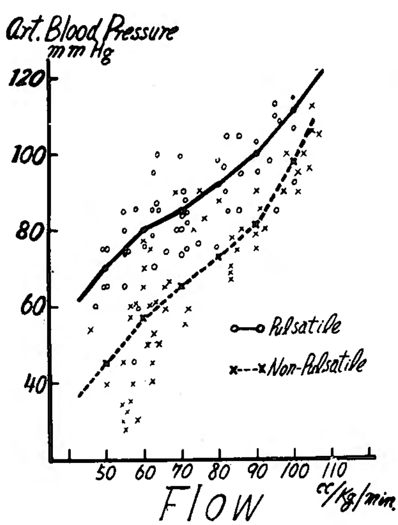

Fig. 4 Comparison of arterial pressure between pulsatile and non-pulsatile flow under the same flow rate. (Integrated mean pressure was adopted in pulsatile group)

A

B

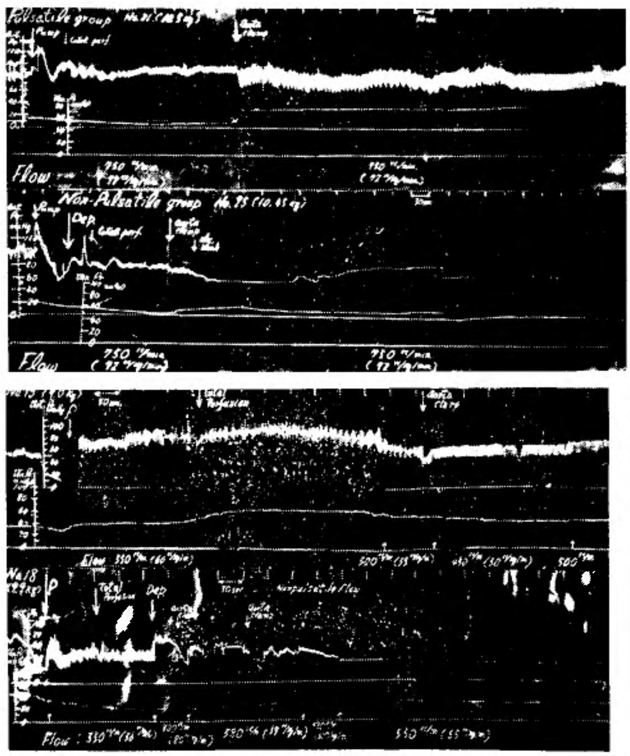

Fig. 5 illustrates arterial pressure during extracorporeal circulation between pulsatile (top row) and non-pulsatile flow (bottom row).
A. Flow rate, 72cc./kg./min.
B. Flow rate, 55~60cc/kg./min.

Under the same flow rate the arterial blood pressure in the pulsatile group was kept approximately 20 mm. Hg higher on the avarage than in the non-pulsatile group. The blood pressure was more adequately maintained in the pulsatile group at flow rates of 60 cc./kg./min. and 75cc./kg./min. as shown in (Fig. 5).

2) Peripheral vascular resistance (Fig. 6)

In the non-pulsatile group the peripheral vascular resistance not only lowered at the beginning but was liable to show a further decrease in the course of time, whereas in the pulsatile group the peripheral vascular tone was adequately maintained throughout the period of extracorporeal circulation.

3) Central venous pressure (Fig. 7)

There was no remarkable difference between both groups. This may be due to the fact that the venous blood is sucked by gravity, hence the venous pressure is not directly influenced by pressure or lack of arterial pulsation. Besides, the non-pulsatile group often showed a decreased venous return which may lead to an unbalance of in- and outflow

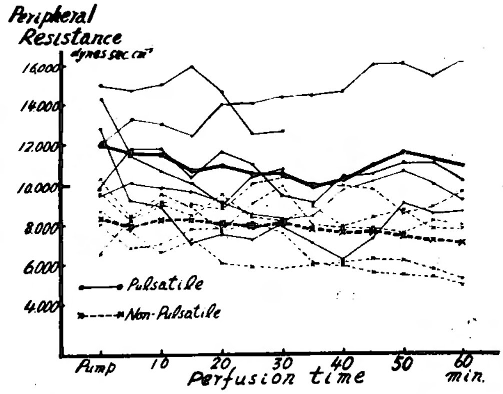

Fig. 6 Peripheral vascular resistance not only lowered but was liable to show a further decrease during extracorporeal circulation.

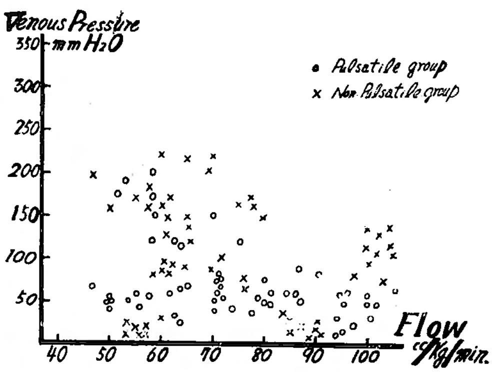

Fig. 7 There was no remarkable difference in venous pressure between both groups.

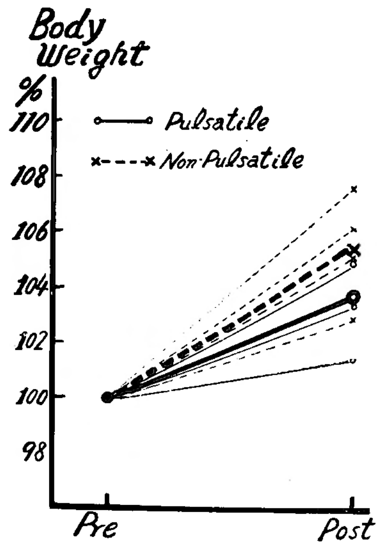

Fig. 8 Change of body weight immediately after perfusion.

of blood. Consequently, the animals of this group exhibited marked increases in body weight at the end of extracorporeal circulation compared with those of the pulsatile group (Fig. 8).

4) Oxygen consumption (Fig. 9)

In the pulsatile group the oxygen consumption was kept nearly at a constant as well as adequate level, whereas in the non-pulsatile group it decreased as the arterial-venous oxygen difference diminished in the course of time. Likewise the pH, and the buffer-base decreased resulting in a marked metabolic acidosis (Fig. 10).

The carbon dioxide output also tended to decrease in this group (Fig. 11). Comparative studies were further conducted between both groups on blood pressure,

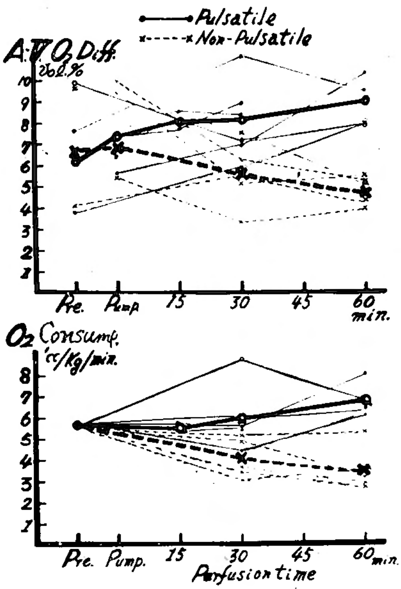

Fig. 9 Oxygen consumption and arterial-venous oxygen difference tended to decrease in the course of time in non-pulsatile group.

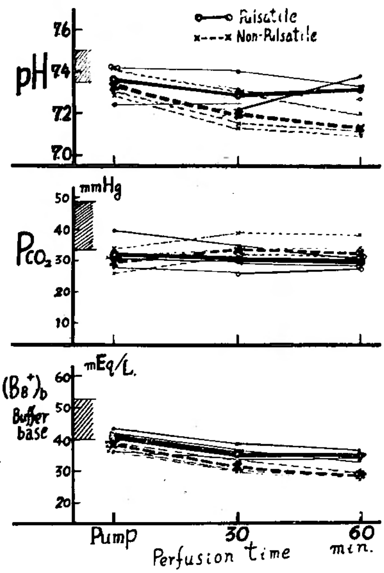

Fig. 10 The pH and the buffer-base decreased and resulted in metabolic acidosis in non-pulsatile group.

oxygen consumption and mean pH value at flow rates of 40 to 60, 61 to 80 and 81 to 110 cc./kg./min., respectively. The studies revealed that obviously better results were obtained in the pulsatile group when the flow rate was less than 80cc./kg./min. (Fig. 12). The results of both groups, however, approximated to each other as the flow rate exceeded 80cc./kg./min.

5) Peripheral circulation

Using the major omentum, change of its volume was recorded with oncometer and alteration of the peripheral blood stream was microscopically observed in vital stage during extracorporeal circulation. As shown in Fig. 13 the volume of the omentum in the pulsatile group exhibited a slight and transient in- or decrease at the beginning of the extracorporeal circulation, then gradually returned to the original value within 15 to 30 minutes, whereas in the non-pulsatile group the volume continued to increase, suggesting the increasing stagnation of blood in the peripheral vascular bed.

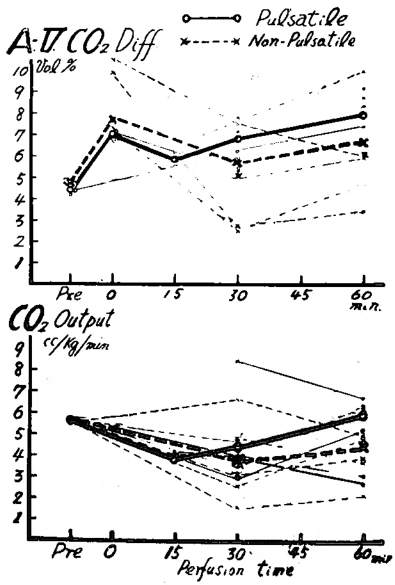

Fig. 11 Carbon dioxide output also tended to decrease in non-pulsatile group.

Fig. 12 Data of both groups seem to approximate to each other as the rate of blood flow exceeds beyond 100cc/kg/min.

Perfusion Rate cc/kg/min	Pulsatile Flow			Non-Pulsatile Flow		
	Art. Pres. (mean) mmHg	O_2Uptake cc/kg/m.	pH (end of perfusion)	Art. Pres. (mean) mmHg	O_2Cons. cc/kg/m.	pH (end of perfusion)
40～ 60	60～ 80	4.5	736 (7.26～7.43)	40～ 60	3.0	7.18 (7.14～7.23)
61～ 80	80～ 95	6.0		60～ 75	4.0	
81～110	95～115	6.5		75～105	5.0	

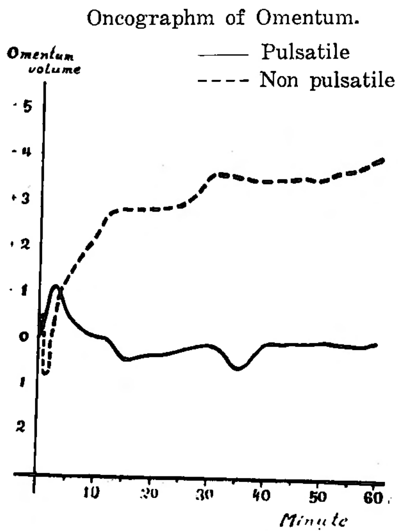

Fig. 13

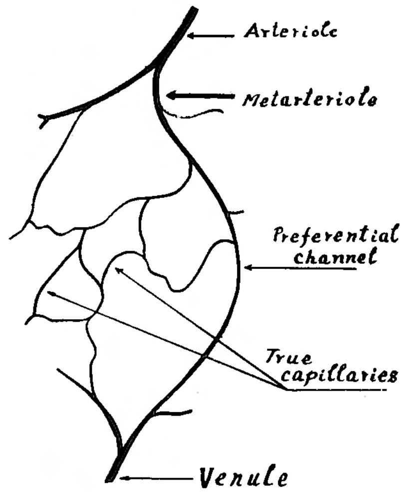

Fig. 14

In vital microscopic study of the peripheral vascular bed, almost compatible results were obtained, i, e. blood cells were adequately distributed from the arteriole to the true capillary in the pulsatile group and the blood stream was slowest in the true capillary, showing the so-called plasma flow.

On the contrary, in the non-pulsatile group the stream gradually slowed down in the true capillary 15 to 20 minutes after the commencement of the extracorporeal circulation and finally it almost ceased. Thus the blood stream chiefly runs through the vessels which Zweifach named the preferential channel (Fig. 14) with a considerable high velocity.

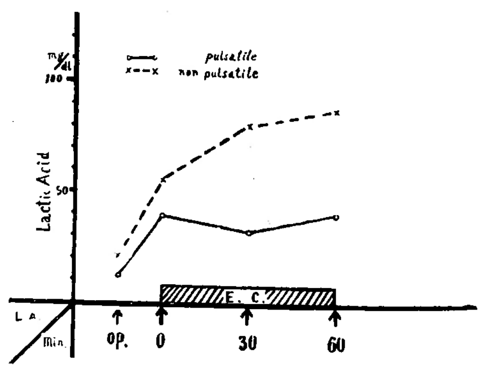

Fig. 15 Blood lactic acid levels between both groups.

6) Blood lactic acid level

Blood lactic acid level also tended to increase in the non-pulsatile group compared with that in the pulsatile group (Fig. 15).

DISCUSSION

In 1955 WESOLOWSKI et al., using non-pulsatile flow, successfully perfused the entire systemic circulation as long as three hours.[6)~8)] They suggested that the pulsatile perfusion is not always necessary. As a matter of fact the pump which is designed to emit a pulsatile flow incorporates a complicated mechanism and is likely to get out of order. Therefore, metal finger type pump, roller type pump etc. which emit nearly non-pulsatile flows have been adopted and employed for clinical use. Our retults, however, clearly indicated the advantage of pulsatile flow. The cause of the discrepancy between WESOLOWSKI's and ours may be the difference in blood flow, i. e. the blood perfused in WESOLOWSKI's experiments was presumably more than 130 cc./kg./min., whereas we perfused 80 to 110 cc./kg./min. This flow rate is nowadays generally adopted. Our results also indicate that data of both groups seem to approximate to each other as the rate of blood flow exceeds beyond 100 cc./kg./min.

Unfavorable circulatory disturbances soon appear under the extracorporeal circulation if non-pulsatile flow of less than 100 cc./kg./min. is employed. The main cause of such unfavorable phenomena seems to be circulatory disturbance of the peripheral vessels, of which the true capillaries play the most important role.

It is also readily understood from the theoretical viewpoint that the non-pulsatile group, because of reduced peripheral vascular resistance, should give rise to arterial hypotension at the same blood flow as in the pulsatile group and this condition results in a normovolemic shock. Various metabolic disturbances may likely occur when the blood flows too rapid mainly through the preferential channel.

SUMMARY

The effectiveness of pulsatile and non-pulsatile blood flow in extracorporeal circulation was experimentally studied and the following results were obtained.

1) The maintenance of arterial blood pressure, peripheral vascular resistance, oxygen consumption, pH and blood lactic acid level were better in the pulsatile group than the non-pulsatile group under the same flow rate.

2) In vital microscopic study of peripheral vascular bed, blood stream gradually slowed down in the true capillary 15 to 20 minutes after the commencement of the extracorporeal circulation in the non-pulsatile group. On the contrary, such disturbance was scarcely observed in the pulsatile group.

3) From our results, it would be safely concluded that the perfusion with pulsatile flow would be a safer procedure when the blood flow is below 100 cc./kg./min. as commonly adopted at present, and particulary when the extracorporeal circulation is continued more than 30 minutes.

Our greatful thanks are given to Professor GORO KAMIMOTO, Faculty of Technology, Kyoto University, for his cooperation and assistance in the construction of the new artery pump.

We also wish to express appreciation to Professor AKIRA INAMOTO, Assistant Professor MASAO FUZITA, Doctor RYOSUKE MURAYAMA, Department of Anesthesiology, Kyoto University Medical School, and Doctor SHUNZO MAETANI for their kindest advice and help.

REFERENCES

1) Andersen, M. N., and Senning, A.: Studies in oxygen consumption during extracorporeal circulation with a pump-oxygenator. Ann. Surg., **148**, 59, 1958.
2) Crafoord, C., Norberg, B., and Senning, A.: Clinical studies in extracorporeal circulation with a heart-lung machine. Acta Chirur. Scandinav., **112**, 220, 1957.
3) Gibbon, J. H., Jr.: The Lewis A. Conner Memorial Lecture. Maintenance of cardiorespiratory functions by extracorporeal circulation. Circulation, **19**, 646, 1959.
4) Halley, M. M., Reemtsma, K., and Creech, O.: Cerebral blood flow, metabolism, and brain volume in extracorporeal circulation. J. Thoracic Surg., **36**, 506, 1958.
5) Starr, A.: Oxygen consumption during cardiopulmonary bypass. J. Thoracic Surg., **38**, 46, 1959.
6) Wesolowski, S. A., and Welch, C. S.: Experimental maintenance of the circulation by mechanical pumps. Surgery, **31**, 769, 1952.
7) Wesolowski, S. A., Fisher, J. H., and Welch, C. S.: Perfusion of the pulmonary circulation by non-pulsatile flow. Surgery, **33**, 370, 1953.
8) Wesolowski, S. A., Sanvage, L. R., and Pinc, R. D.: Extracorporeal circulation: The role of the pulse in maintenance of the systemic circulation during heart-lung by-pass. Surgery, **37**, 663, 1955.

和文抄録

体外循環の実験的研究

(脈動の有無が体外循環中の生体に及ぼす影響について)

京都大学医学部外科学教室第2講座 (指導：青柳安誠教授)

緒方 武・井田喜三・野々山 明・武田 惇・佐々木秀郎

1955年に Wesolowski は動物実験で，無脈動流を用いて3時間に亘る体外循環を行つても生体には殆ど悪影響がみられなかつたと報告した．以来，臨床上用いられている動脈ポンプには，脈動という点を特に考慮して作られたものが少ない．しかしながら最近体外循環の時間が長びくにつれて，生体に不利な種々の現象が起ること，例えば動脈血圧の低下や送・脱血の不均衡，代謝性アチドージスの発生等が注目され初めた．その原因に就いては未だ不明の点が多いのである．われわれはそのような不愉快な現象の起る原因の一つとして，体外循環に切り替えた時の脈動の減弱乃至消失を考え，体外循環中の脈動の有無が生体に及ぼす影響を実験的に検討した．即ち，体重8～12kgの成熟雑犬を用い，本学工学部，神元教授の指導によつて作製した新型脈動式動脈ポンプを使用し，1時間乃至1時間半の完全体外循環を行つて次のような結果をえた．

1) 動脈血圧，末梢血管抵抗，酸素消費量，pH，血液乳酸濃度等は何れも同一流量に於て，脈動流を用いた時の方が遙かに良好である．

2) 末梢循環に関しても，大網膜を用いたOncography に於ては，脈動流の場合の方が容積変化が少ない．また生体顕微鏡観察下の末梢血管領域に於ては，網状毛細管の血流状態は脈動流では略々正常に維持されるに反し，無脈動流では次第に悪化する．

3) 環流々量が100cc/kg/min以下に減少する程，また，体外循環が長時間に亘る程，無脈動流による障害は益々著しくなる．

4) 以上の結果から臨床上，100cc/kg/min 以下の流量で環流する時，或は体外循環が30分以上に及ぶ時には脈動流を用いた方が遙かに安全な体外循環を行いうるものと考える．