Evaluation of Mechanical Left Ventricular Assistance with Left Atrium to Aorta Bypass in Dogs

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SATO, N., KAGAWA, Y., NITTA, S., MOHRI, H. and HORIUCHI, T. Evaluation of Mechanical Left Ventricular Assistance with Left Atrium to Aorta Bypass in Dogs. Tohoku J. exp. Med., 1981, 134 (4), 375-384 — Effects of the left heart bypass (LHB) by the left atrium (LA) to the aorta (AO) shunt on the heart were evaluated by measuring such parameters as tension time index (TTI), diastolic pressure time index (DPTI), DPTI/TTI ratio, coronary blood flow and myocardial oxygen consumption (MVO₂) in open-chest dogs. A pneumatically driven bypass pump made of polyurethane was utilized in this study. No significant change of MVO₂ was observed with surgical maneuver to connect the LA-AO LHB pump to experimental animals. During synchronous pumping of LHB, TTI decreased by 35%, MVO₂ decreased by 56% of the control and DPTI/TTI ratio increased by 79%. However, coronary flow decreased by 35%, presumably due to autoregulation mechanism of the coronary circulatory system. Both synchronous and asynchronous LHB demonstrated the same level of effect in volume unloading. However, significant diastolic augmentation was noted only in the former. LA-AO LHB, which has a sufficient supporting effect and does not damage the ventricular wall, was considered to be very useful for temporary support for the failing heart, especially for postoperative low output state. — left ventricular assistance; TTI; DPTI; MVO₂; coronary blood flow

Left heart bypass, a method of mechanical assistance for severe left heart failure, has been utilized clinically (DeBakey 1971; Litwak et al. 1976; Norman 1977; Pierce et al. 1978) and some have reported satisfactory results (DeBakey 1971; Litwak et al. 1976). Several methods of left heart bypass have been developed and they are divided into two main groups by the sites of blood drainage, that is, the left atrium to aorta bypass group (LA-AO LHB) and the left ventricle to aorta bypass group (LV-AO LHB). LA-AO LHB appears not to suppress left ventricular function and synchronous pumping to the natural heart rhythm is not mandatory with this method. In experimental set up with a normal heart, however, LA-AO LHB occasionary fails to drive a sufficient blood volume for the bypass. Thus, skepticism was raised for the use of LA-AO LHB, and many investigators have experimented LV-AO LHB (Hughes et al. 1975; Watanabe et al. 1975; Pierce et al. 1978). It is obvious that the LV-AO LHB is able to replace most of the cardiac
output with ease and is able to reduce left ventricular pressure and volume load to a great extent. However, LV-AO LHB also carries some shortcomings. The insertion of an inflow cannula to the left ventricle may affect function of the failing ventricle. In addition, fixation of the inflow cannula to ventricular wall suppress the diastolic recoiling of the ventricle, which is thought to be one of the most important factors of the ventricular performance (Rushmer 1970). The purpose of this study is to evaluate LA-AO LHB using our sack type bypass pump and to document effects of such pumping on canine hearts.

**Materials and Methods**

*The device and driving system.* A pneumatically driven type bypass pump, bearing semilunar tricuspid valves as inflow and outflow valves was utilized. All parts of the pump, including valves, were fabricated with polyurethane by an injection mold method. The maximum stroke volume was approximately 100 ml and the maximum cardiac output was 8 liters per min. The pump was driven by compressed air and vacuum, which was controlled by an electronic pulse generator and a three-way solenoid valve. Modes of pumping were asynchronous and synchronous to beating of the natural heart. The R wave of electrocardiogram was used as a trigger in the synchronous mode. Pumping rates, and duration of systole and diastole as well as delay time from R-wave can be controlled independently with manual operation.

*Experimental procedure.* Fifteen mongrel dogs weighing 16-25 kg were anesthetized with intravenous pentobarbital sodium. Under controlled respiration with a volume-limited respirator, bilateral pleural cavities were entered through the IVth intercostal space. A silastic cannula, 6 mm in external diameter, was inserted into the coronary sinus via the right atrial appendage and the tip of the cannula was fixed with an externally placed circumferential ligature. The other end of the cannula was inserted into the right atrium. Flowmetry and sampling of coronary venous blood were done through a T-tube, which was interposed at the middle portion of the cannula (Fig. 1-left). After intravenous administration of 1 mg/kg of heparin, the bypass pump was connected to the descending aorta and left atrium in the following manner. A T-shaped outflow cannula with an electromagnetic flow probe was inserted into the descending aorta in a fashion as shown in Fig. 1-right. After intravenous administration of 2 mg/kg of xylocaine, an inflow cannula with 10 mm internal diameter for the device was inserted into the left atrial cavity via the left atrial appendage and secured with a pursestring suture. Inflow and outflow cannulae were connected to the bypass pump and all air was evacuated from the system. Another electromagnetic flow probe was placed around the pulmonary trunk to measure a total cardiac output. Aortic and left ventricular pressures, cardiac output, output of the bypass pump and electrocardiograms were continuously monitored during entire experimental procedures with a multichannel recorder. Asynchronous pumping was carried out at a rate of 50 to 80 beats/min. The driving pressures were 150 to 180 mmHg during systole and -30 mmHg during diastole, respectively. Synchronous pumping was carried out using a delay time of approximately 30% of the R-R interval from R-wave of EKG so that peak ejection phase of the pumping fell at the diastolic phase of the natural heart beat. In the synchronous pumping, the driving pressure required was as high as in the asynchronous pumping during systole, whereas a high vacuum pressure, approximately 60% more than asynchronous pumping, was needed during diastole to obtain the same bypassed blood volume of the latter.

In this study, tension time index (TTI), diastolic pressure time index (DPTI), endocardial viability ratio (EVR), myocardial oxygen consumption (MVO₂) and coronary blood flow (CBF) during synchronous and asynchronous LA-AO LHB were studied. MVO₂ and CBF before and after surgical procedure of connection of the LHB pump were compared in order
to explore the effect of surgical stress on these parameters as was previously reported (Wakabayashi et al. 1975).

TTI was delivered by planimetry of systolic phase of the left ventricular pressure tracings, and DPTI was delivered by the planimetry of diastolic phase of the aortic pressure tracings. TTI, DPTI and DPTI/TTI ratio (EVR) were calculated as mean of ten cardiac cycles. The coronary sinus flow was substituted for the coronary blood flow and obtained by occluding the coronary sinus cannula for 30 sec and allowing the blood to flow into a measuring cylinder via the T-tube.

The MVO$_2$ was calculated by the formula derived from Fick’s principle.

$$\text{MVO}_2 = 1.34 \times \frac{\text{SAO} - \text{Scs}}{100} \times \frac{\text{Hb}}{100} \times \frac{\text{CBF}}{\text{Heart weight}} \times 100$$

Where the SAO and Scs represent an oxygen saturation of the arterial and the coronary sinus blood, respectively. Serum hemoglobin contents were measured by the cyanomethohemoglobin method. Student-t test was applied for the statistical analysis.

**RESULTS**

CBF and MVO$_2$ before and after surgical maneuvers of connecting the bypass pump to experimental animals are demonstrated in Table 1, and Figs. 2 and 3. No significant changes were observed in both parameters.

Fig. 4 demonstrates representative pressure tracings of the left ventricle and aorta, before and during asynchronous left heart bypass pumping of approximately 60% bypass ratio. The asynchronous left heart bypass was performed in 11 cases and mean values of each parameter obtained before and during asynchronous LHB pumping are demonstrated in Table 2 and Figs. 2, 3 and 5. TTI, MVO$_2$ and CBF decreased significantly by 35% ($p<0.005$), 51% ($p<0.005$) and 48% ($p<$
DPTI/TTI ratio was increased by 50% ($p<0.005$), although no significant change of the DPTI was observed. Fig. 6 demonstrates representative pressure tracings of the left ventricle and aorta before and during synchronous LHB pumping of approximately 60% bypass ratio. The synchronous LHB pumping was performed in 6 cases and mean values of each parameters are summarized in Table 2 and Figs 2, 3 and 5. During synchronous LHB pumping, TTI decreased by 32% ($p<0.005$), DPTI increased by 11% ($p<0.05$) and the DPTI/TTI ratio increased by 71% ($p<0.005$). There were no significant differences of TTI between synchronous and asynchronous pumping groups. DPTI during synchronous LHB was significantly higher than that during asynchronous LHB ($p<0.01$). DPTI/TTI ratio of the synchronous pumping group was significantly higher than that of the asynchronous pumping group ($p<0.05$). The synchronous pumping demonstrated a slightly higher CBF and lower $\text{MV}_2$ than the asynchronous pumping, but their differences were statistically insignificant.

### Table 1. $\text{MV}_2$ and CBF before and after surgical procedures

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Surgical procedures</th>
<th>Significance</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Before (n=7)</td>
<td>After (n=7)</td>
</tr>
<tr>
<td>$\text{MV}_2$ ml/min/100 g</td>
<td>3.52±0.70</td>
<td>3.42±0.72</td>
</tr>
<tr>
<td>CBF ml/min</td>
<td>51±6</td>
<td>52±7</td>
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Numbers in the table are means±standard deviations. N.S. stands for not significant.

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![Fig. 2](image1.png)  ![Fig. 3](image2.png)

**Fig. 2.** The effect of cannulation of LHB pump and asynchronous (asynch) and synchronous (synch) LHB pumping on myocardial oxygen consumption ($\text{MV}_2$).

**Fig. 3.** The effect of cannulation of LHB pump and asynchronous (asynch) and synchronous (synch) LHB pumping on coronary blood flow (CBF, CF).
Scattergrams of the CBF and TTI or DPTI are shown in Figs. 7A and 7B. A high correlation between the CBF and TTI ($r=0.79$, $p<0.01$) and no correlation ($r=0.10$, $p>0.05$) between the CBF and DPTI were seen.

A scattergram between the MV$_{O_2}$ and TTI is shown in Fig. 8, demonstrating a high correlation between both parameters. A larger correlation coefficient was obtained by a logarithmic curve fitting study ($r=0.82$, $p>0.01$) than by a linear

![Fig. 4. Representative tracings of left ventricular (LV) and aortic (Ao) pressure during asynchronous LHB pumping. Shaded areas indicate systolic and diastolic phase of LV and Ao pressure, respectively. TTI, DPTI and DPTI/TTI calculated in this case are shown on the tracings.](image)

![Fig. 5. Effect of asynchronous and synchronous LHB pumping on TTI, DPTI and DPTI/TTI. For statistical tests, see text or Table 2.](image)
correlation study \( (r=0.77, \ p<0.01) \). However, statistical significance was not noted in the difference between the two correlation coefficients.

**DISCUSSION**

Aims of the LHB are directed to reduction of the cardiac work and myocardial oxygen consumption, as well as the increase of the coronary blood flow. For
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clinical application, such as temporary support for a failing heart, especially for the damaged myocardium, a lesser invasive method of the LHB should be selected. There are many controversial opinions regarding the superiority between LA-AO LHB and LV-AO LHB, although it is generally accepted that LV-AO LHB has the more beneficial effect, since the LV-AO LHB can bypass a larger amount of blood than the former.

Many circulatory indices have been used to evaluate supportive effects of an assisted circulatory device and levels of myocardial oxygen consumption are thought to be one of the better parameters which gives us more direct information. Dennis et al. (1962) first demonstrated a decrease of MVO2 by 18% when an inflow cannula was placed in the left atrium and by 47% in the left ventricle. Miller performed comparative studies of LA-AO and LV-AO LHB and demonstrated

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**Fig. 7.** Scattergram of coronary blood flow plotted against DPTI and TTI. TTI showed high correlation with CBF (CF), on the other hands, less correlation was noted between DPTI and CBF.

**Fig. 8.** Scattergram of TTI plotted against myocardial oxygen consumption. Solid curve indicates the result of a logarithmic curve fitting study ($r=0.82$, $p<0.01$, $y=744 \ln x+1142$) and a dotted line indicates the result of a linear fitting study ($r=0.77$, $p<0.01$, $y=316x+960$).
similar results to that of Tamura's. Watanabe et al. (1975) using LV-AO LHB, described a decrease of $\text{MVO}_2$ by 67% of the control. Wakabayashi et al. (1975) reported approximately 30% decrease of $\text{MVO}_2$ by surgical preparation alone. They also noted a significant reduction in $\text{MVO}_2$ during combined LV-AO and LA-AO LHB, although LA-AO alone did not result in a significant decrease of $\text{MVO}_2$. In our experiments on LA-AO LHB, surgical preparation alone produced no significant changes of $\text{MVO}_2$. The change observed by Wakabayashi et al., therefore, may be caused by much larger surgical stress in which the cannulation was made not only to the left atrium but also to the left ventricle.

Many controversial results have been reported regarding influence of the LHB on CBF. Sato and Glenn (1970), Schenk et al. (1964) and Wakabayashi et al. (1975) reported no significant change in either CBF or $\text{MVO}_2$ during LHB. Tamura reported a slight increase of CBF and significant reduction of $\text{MVO}_2$, but on the contrary, Dennis et al. (1963) and Miller (1974) described a decrease of CBF by 30 to 40% and observed a significant reduction of $\text{MVO}_2$. In our study, both CBF and $\text{MVO}_2$ decreased significantly during LA-AO LHB. The CBF decreased by 20% of the control, despite increased DPTI or coronary perfusion pressure, during synchronous LHB. A decrease in $\text{MVO}_2$ was also noted in proportion to the decrease of CBF. The coronary blood flow is believed to be regulated by many factors, especially by both perfusion pressure and the myocardial oxygen demand (Rubio 1975). Nevertheless, from our experiments it is highly likely that CBF was determined to a greater extent by myocardial oxygen demand than by coronary perfusion pressure.

Changes in TTI have long been used to evaluate the reduction of myocardial performance with circulatory assist devices. Some investigators observed reduced TTI by LA-AO LHB (Nitta et al. 1973), but Miller et al. (1974) showed no decrease of TTI while $\text{MVO}_2$ substantially decreased. With properly driven LV-AO LHB, the left ventricle is nearly completely decompressed, and thus, the TTI decreases by 70% of the control reportedly (Hughes et al. 1975; Watanabe et al. 1975). Even if a total bypass is obtained with LA-AO LHB, the left ventricular myocardium will continue isovolumic contraction and TTI might not show substantial decrease. Normal hearts do not depend upon the assist circulatory devices and TTI decreases little, while failing hearts more likely depend on LHB during pumping with left ventricular pressure reduced. Thus, in clinical set up for failing heart, substantial decrease of TTI will be expected during LA-AO LHB.

Buckberg et al. (1972) proposed to use DPTI/TTI, which represents myocardial supply/demand relationship, as the endocardial viability ratio. Hughes et al. (1975), using their LV-AO LHB (abdominal left ventricular assist device), have demonstrated an increase of the DPTI/TTI ratio by five times of the control in normal hearts and more than thirty times in ischemic hearts. Our data showed only two times increase of the DPTI/TTI ratio, since TTI did not change greatly with LA-AO LHB. During asynchronous pumping, the effect of diastolic augmentation was not observed in most cases and DPTI and DPTI/TTI ratio
decreased slightly. On the other hand, properly driven synchronous pumping caused a marked increase in the aortic diastolic pressure and DPTI/TTI ratio substantially increased. The decrement of TTI and MVO₂ during synchronous and asynchronous LHB under the same bypass ratio were equal. Under this condition, an increased DPTI or coronary perfusion pressure due to diastolic augmentation of synchronous pumping, resulted in an increase of the coronary flow. Consequently, a synchronous LHB proven to be superior to an asynchronous pumping for its diastolic augmentation and a possibility of increasing the coronary blood flow. However, the asynchronous or alternative synchronous LHB will also be very effective to release volume load of the heart with dysrhythmia or tachycardia.

The most probable and appropriate objects of clinical application of LHB are for postoperative low cardiac output syndrome, especially patients who cannot be weaned from cardiopulmonary bypass, despite the use of intra-aortic balloon pumping. In such cases, only 10 to 30% of volume unloading of the left ventricle by means of cardiopulmonary bypass is extremely effective to maintain reasonable circulatory condition. As was reported previously (Sato et al. 1977), complete decompression of the left ventricular cavity might depress the right ventricular contraction. Therefore, LHB in the form of LV-AO LHB which unloads a large amount of blood, may not be necessary in patients with postoperative low output sites. In more severely failed hearts, the LA-AO LHB can increase its bypass ratio to the near total since left atrial pressure usually increase as cardiac failure progresses.

In addition, the LV-AO LHB can produce local ischemia or asynergy around the insertion site of an inflow cannula, and may require laparotomy to place the apparatus, since pericardial space is too small to accomodate an apical inflow cannula without acute angulation. Thus, LV-AO LHB might not be accepted as the first choice for clinical application of left ventricular assist device, despite its highly beneficial effects. And LA-AO LHB may be the device of choice for patients with postoperative low output syndrome which is unresponsive to intra-aortic balloon pumping, and LV-AO LHB should be reserved for cases of severer myocardial failure.

References


