Comparison of Hemodynamic Effects of Enhanced External Counterpulsation and Intra-Aortic Balloon Pumping in Patients With Acute Myocardial Infarction

Isao Taguchi, MD, Kenichi Ogawa, MD, Akitugu Oida, MD, Shichirou Abe, MD, Noboru Kaneko, MD, and Hideaki Sakio, MD

Enhanced external counterpulsation (EECP), a novel form of sequenced external counterpulsation, was the type of external counterpulsation used in our study. A beneficial effect of EECP on patients with angina pectoris has been reported in a series of case studies[1–5] and proved by a prospective, randomized, multicenter controlled study.[6] Over the years, external counterpulsation has been improved to achieve more effective diastolic augmentation by applying pressure on the legs sequentially from the lower legs to the lower and upper thighs. This action propels arterial blood in a retrograde fashion to the heart, increases venous return and, consequently, cardiac preload.[7] Several precise noninvasive observations of hemodynamic effects of EECP using fingertip plethysmography and/or Doppler echocardiography have documented an increase in cardiac output, presumably because of increased venous return.[8,9] However, the hemodynamic changes evoked by EECP have not been measured by direct hemodynamic monitoring, because invasive monitoring is not usually acceptable during EECP for outpatients.[10] The aim of this study, therefore, is to measure the hemodynamic effects of EECP compared with intra-aortic balloon pressure (IABP) using traditional hemodynamic monitoring.

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The study was composed of 39 patients with acute myocardial infarction. Direct balloon coronary angioplasty was performed in all patients successfully within 12 hours after onset of chest pain. Patients were then admitted into our coronary care unit. Intra-aortic balloon pumping was administered to 12 patients (IABP group) at the cardiac catheterization laboratory because of intracoronary thrombosis observed during coronary angioplasty. All patients were given heparin, keeping activated clotting time within 200 to 300 seconds while in the coronary care unit. EECP was performed in 24 male and 3 female patients in Killip class 1 clinical condition 2 or 3 days after admission. Four patients did not complete the 60-minute course of EECP treatment because of intolerance, described as an uncomfortable feeling due to mechanical vibration during EECP, and were excluded from analysis. Consequently, 23 patients completed the 60-minute course of EECP treatment and were analyzed (EECP group). Informed written consent was obtained from all patients in the EECP and IABP groups. The study was authorized by the review board of the university hospital and performed in accordance with the Declaration of Helsinki. Table 1 lists patient characteristics including medications of the 2 groups. No difference in age, left ventricular function (estimated by left ventriculography), site of coronary lesion, Killip class, or medications was observed between the 2 groups.

TABLE 1 Patient Characteristics

Variable	EECP (n = 23)	IABP (n = 12)
Age (yrs)	61 ± 8	62 ± 9
Men	21 (91.3%)	9 (75.0%)
Site of coronary lesions		
Left anterior descending artery	16 (69.6%)	6 (50.0%)
Left circumflex artery	2 (8.7%)	1 (8.35%)
Right coronary artery	5 (21.7%)	5 (41.7%)
Peak creatine phosphokinase (U/L)	3,100 ± 2,469	4,320 ± 3,440
Left ventricular ejection fraction	51.5 ± 11.7%	57.4 ± 12.3%
Killip class on admission		
I	17 (73.9%)	9 (75.0%)
II	6 (26.1%)	3 (25.0%)
III	0	0
IV	0	0
Drugs		
Nitroglycerin	23 (100%)	12 (100%)
ACE-I	22 (95.7%)	11 (91.7%)
β blocker	4 (17.4%)	2 (16.7%)

Values are expressed as mean ± SD or number (%).
ACE = angiotensin-converting enzyme.

Vasomedical (Westbury, New York) supplied the EECP devices. The equipment consisted of an air compressor, a control console, a treatment table containing the air flow valves, and 2 sets of 3 air cuffs for calves and lower and upper thighs. These cuffs are wrapped around the patient's legs, 1 set on each leg. Approximately 300 mm Hg of pressure is applied via the cuffs to the patient's lower legs in a sequence synchronized with the cardiac cycle. In early diastole, pressure is applied sequentially from the lower legs to the lower thighs and upper thighs to propel arterial blood back to the aorta, and venous blood to the right heart via the inferior vena cava. The result is diastolic augmentation, i.e., an increase in arterial blood pressure and retrograde aortic blood flow during diastole, and increased preload.[8] At end-diastole, air is released instantaneously from all cuffs to remove the externally

From the Department of Cardiology and Pneumology, and the Intensive Care Unit, Dokkyo University School of Medicine, Tochigi, Japan. Dr. Ogawa's address is: Department of Cardiology and Pneumology, Dokkyo University School of Medicine, 880 Kitakobayashi, Mibu, Tochigi 321-0293, Japan. E-mail: k-ogawa@dokkyomed.ac.jp.
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TABLE 2 Hemodynamic Effects of EECP and IABP

	Baseline	15 min	30 min	45 min	60 min	60 min After
Heart rate (beats/min)						
EECP	85 ± 13	87 ± 15	85 ± 14	85 ± 15	85 ± 15	84 ± 13
IABP	90 ± 15	89 ± 14	88 ± 16	90 ± 16	89 ± 15	91 ± 12
Right atrial pressure (mm Hg)						
EECP	6.4 ± 3.3	9.8 ± 4.0†‡	9.0 ± 3.6*	8.1 ± 3.4	7.9 ± 3.2	5.5 ± 3.9
IABP	6.8 ± 2.3	6.8 ± 2.2	6.8 ± 2.2	7.3 ± 2.3	7.2 ± 2.3	7.3 ± 2.3
Pulmonary capillary wedge pressure (mm Hg)						
EECP	9.0 ± 4.0	12.6 ± 5.3†	11.8 ± 4.4*	11.7 ± 5.5	10.7 ± 4.8	6.0 ± 3.0‡
IABP	11.5 ± 3.5	11.5 ± 4.3	11.3 ± 3.9	11.2 ± 4.1	11.4 ± 4.2	11.3 ± 4.0
Cardiac index (L/min/cm^2)						
EECP	3.3 ± 0.8	3.6 ± 0.6	3.7 ± 0.7	3.9 ± 0.7*	4.1 ± 0.8†‡	3.5 ± 0.9
IABP	3.4 ± 0.8	3.3 ± 0.8	3.3 ± 0.7	3.4 ± 0.8	3.4 ± 0.6	3.2 ± 0.7
Area under artery pressure tracing in systole (mm Hg · s)						
EECP	29 ± 5	27 ± 4‡	28 ± 4§	28 ± 4§	27 ± 3‡	29 ± 5
IABP	28 ± 4	21 ± 5†	22 ± 3†	22 ± 3†	22 ± 4†	28 ± 4
Area under artery pressure tracing in diastole (mm Hg · s)						
EECP	33 ± 9	44 ± 10†	45 ± 10†	44 ± 10†	44 ± 11†	32 ± 9
IABP	30 ± 9	40 ± 14	40 ± 12	41 ± 13*	41 ± 14*	30 ± 9
Systolic systemic vascular resistance (dynes · s/cm^5)						
EECP	1,419 ± 349	1,168 ± 256†	1,171 ± 268†	1,133 ± 206†	1,141 ± 286†	1,324 ± 318
IABP	1,373 ± 202	1,110 ± 198*	1,146 ± 209*	1,117 ± 267*	1,130 ± 234*	1,429 ± 331

*$p < 0.05$ versus baseline; †$p < 0.01$ versus control; ‡$p < 0.01$ versus IABP.
Values are expressed as mean ± SD.

applied pressure, allowing the compressed vessels to reconform. Systolic unloading is therefore accomplished by reducing vascular impedance in the systolic phase.

To assess the hemodynamic effect of EECP and IABP, heart rate, right atrial pressure, pulmonary capillary wedge pressure, and cardiac index were measured by continuous cardiac output computation based on thermodilution principals (Vigilance, Baxter Edwards Critical-Care, Irvine, California) inserted through a right or left subclavian vein. Direct radial artery pressure tracing was used to measure the areas under the artery pressure curves in systolic and diastolic phases. Systolic systemic vascular resistance was calculated as mean systolic blood pressure divided by stroke volume and multiplied by 80.

EECP was administered to the patients in the EECP group for 60 minutes. All parameters were measured before and at 15, 30, 45, and 60 minutes after starting EECP, and 60 minutes after stopping EECP. In the IABP group, baseline measurements were obtained >60 minutes after setting of minimal IABP effect (1:8 inflation ratio to the cardiac contraction with minimal applied pressure) to achieve a static hemodynamic condition and to avoid blood clots on the IABP balloon surface. After obtaining baseline measurements, IABP treatment with 1-by-1 inflation ratio and full inflation pressure was applied. Additional measurements were obtained at 15, 30, 45, and 60 minutes after starting full support of IABP and 60 minutes after returning to a minimal IABP effect setting.

Values are expressed as mean ± SD. Statistical analysis was performed using analysis of variance to examine changes in hemodynamic parameters in each group. The unpaired *t* test was used to test the difference of each hemodynamic parameter between 2 groups at the same measurement time point. Statistical significance was achieved at the 5% level ($p < 0.05$).

No adverse effect, including bleeding from cannulation sites or interference with oxygenation estimated by oxymetry of arterial blood, was observed in any analyzed subject. Table 2 shows the mean ± SD of hemodynamic parameters at each time point of measurement in each group.

Mean values of heart rate did not change significantly in either group before, during, and after treatments. Mean values of heart rate at baseline and during and after treatments did not show significant differences between the 2 groups.

Mean values of right atrial pressure increased significantly at 15 and 30 minutes after starting EECP compared with values at baseline, then decreased gradually. There was no significant increase in right atrial pressure 45 and 60 minutes after starting EECP compared with baseline value. Although mean values of right atrial pressure did not change in the IABP group, there was no significant difference at any measuring time point between 2 groups, except at 15 minutes after starting treatment.

Mean values of pulmonary capillary wedge pressure in the EECP group increased significantly at 15 and 30 minutes after starting EECP, and then decreased gradually, but no significant change was seen in the IABP group. Differences of mean values between the 2 groups were not significant at baseline and during treatment. However, the mean value at 60

minutes after stopping treatment was significantly lower in the EECP group than in the IABP group.

Mean values of cardiac index increased significantly at 45 and 60 minutes after starting treatment compared with the baseline value in the EECP group. However, no significant change was observed in the IABP group. The mean value of cardiac index at 60 minutes after starting treatment in the EECP group was significantly greater than that in the IABP group.

Mean values of the areas under the artery pressure curves during the diastolic phase increased significantly compared with baseline value at every measuring point during treatment in the EECP group, and at 45 and 60 minutes in the IABP group. There was no significant difference between the 2 groups at any measuring point.

Mean values of the areas under the artery pressure curves during the systolic phase decreased significantly during treatment compared with baseline in the IABP group. No significant change was observed, however, in the EECP group. Mean values in the IABP group were significantly lower than those in the EECP group at every measuring point during treatment.

Mean values of systolic systemic vascular resistance decreased significantly during treatment compared with baseline values in both groups. No significant difference in systolic systemic vascular resistance between the 2 groups was observed at any measuring point.

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Results of our study showed that EECP has effects on the systemic arterial system similar to those of IABP. The changes in area under the arterial pressure tracing during the diastolic phase, which represents diastolic augmentation, increased similarly in the EECP and IABP groups. The area under the arterial pressure tracing in the systolic phase, which represents systolic unloading, did not decrease significantly in the EECP group. On the other hand, systemic vascular resistance during systole decreased in the EECP group similar to that in the IABP group. An increase in cardiac output, as shown by an increase in cardiac index, presumable obscured the decrease in area under arterial pressure tracing in the systolic phase. Increased cardiac preload, shown by increases in right atrial and pulmonary capillary wedge pressures, caused an increase in cardiac index in the EECP group. The increase in these pressures is apparently because of an increase in venous blood propelled from the lower legs and buttocks during treatment with EECP.

This effect on venous blood flow may be beneficial in terms of increase in cardiac output in low output syndromes. On the other hand, even a transient increase in pulmonary wedge pressure may not be favorable for patients with marked pulmonary congestion. The trend of changes in right atrial and pulmonary capillary wedge pressures during EECP treatment appears to decrease along with the increase in cardiac index. Presumably, an initial blood shift to the pulmonary vascular bed, pulmonary vein, left atrium, and left ventricle is gradually eliminated by being pumped out with the assistance of the decrease in systemic vascular resistance during systole. The increases from baseline value in both pressures became nonsignificant 45 and 60 minutes after starting treatment. This trend may indicate that when treatment continues for longer periods (i.e., 120 or 180 minutes), both pressures will decrease. These findings support an optimistic prediction that EECP is feasible for use in patients with acute heart failure as a noninvasive mechanical cardiac support procedure.

A limitation of our study is that the hemodynamic state of the subjects was stable. We did not include patients with pulmonary congestion or low-output syndrome. Although previous clinical reports mentioned that pulmonary wedge pressure decreased in patients with acute myocardial infarction after EECP treatment,[11] cardiac preload increased at the early phase of the treatment. An increase in venous return in patients with high pulmonary capillary wedge pressure due to left ventricular dysfunction may increase lung congestion during EECP treatment. Further studies using patients with more severe acute heart failure are needed to enable broader evaluation of EECP under these circumstances.

The hemodynamic effects of EECP were similar to those of IABP in diastolic augmentation. However, right atrial pressure, pulmonary capillary wedge pressure, and cardiac index increased during EECP in contrast to IABP. Consequently, these effects suggest that EECP increases venous return, raises the cardiac preload, and increases cardiac output.

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