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Intra-aortic balloon pumping: effects on left ventricular diastolic function

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Abstract

Objective: The intra-aortic balloon pump is the most widely used form of temporary cardiac assist and often utilised in patients before and after cardiac surgery. Several effects of balloon counter-pulsation have been reported previously, but its effect on left ventricular diastolic function has not been thoroughly investigated. The aim of this study is to examine the effect of the intra-aortic balloon pump on left ventricular wall motion and transmitral flow. **Methods:** We studied 20 patients in the intensive care unit, less than 36 h following cardiac surgery. We recorded left anterior descending coronary artery and transmitral E-wave flow velocities using transesophageal echocardiography pulsed Doppler. We also recorded left ventricular long axis free-wall movement using M-mode. The intra-aortic balloon pump was set to full augmentation and recordings were made at pumping cycles 1:1, 1:2, 1:3, and when the pump was on stand-by, leaving a minimum of 5 min between the pumping modes to allow the return to control conditions. In order to eliminate time effects, the sequence of recording was varied between patients using a 4 by 4 Latin-square. **Results:** The peak diastolic left anterior descending coronary artery and transmitral E-wave flow velocities, and left ventricular free-wall early diastolic lengthening velocity increased significantly with intra-aortic balloon pumping cycles 1:1, 1:2 and 1:3 compared to their value with the pump on stand-by, all $P < 0.001$. The increase in peak transmitral E-wave flow velocity correlated with the increase in peak left anterior descending coronary artery diastolic flow velocity ($r = 0.74$, $P = 0.02$), and with the increase in left ventricular free-wall early diastolic lengthening velocity ($r = 0.80$, $P < 0.001$). **Conclusion:** Using the intra-aortic balloon pump post-cardiac surgery significantly increases peak diastolic left anterior descending coronary artery flow velocities and left ventricular free-wall early diastolic lengthening velocity, whose increase explains the increase in peak transmitral E-wave velocity. Although coronary flow is epicardial and mitral flow is intracardial, their close relationship suggests an improvement in left ventricular diastolic function with intra-aortic balloon pump.

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Keywords: Intra-aortic balloon pump; Diastolic function; Coronary flow; Mitral flow

1. Introduction

The intra-aortic balloon pump (IABP) is the most widely used form of temporary cardiac assist, and its benefits have been repeatedly acknowledged in patients with impaired ventricular function [1–3]. IABP is frequently used in intensive care units for patients suffering from cardiogenic shock [4] and unstable angina [5]. It is also used in patients pre-operatively [6,7], intra-operatively [8,9] and post-operatively [10,11] to support haemodynamic insufficiency. The principle timing of balloon counter-pulsation is to

inflate the balloon after aortic valve closure in early diastole and to deflate it just before the aortic valve opens in the succeeding beat. However, the exact and optimum timing of inflation and deflation can vary between patients and with different pumps. The inflation of the balloon in early diastole displaces an amount of blood back towards the left ventricle (LV), increasing the pressure in the ascending aorta and thus enhancing coronary flow. Deflation of the balloon in late diastole reduces aortic pressure and consequently LV after-load for the succeeding ejection.

Augmentation of coronary flow as one of the primary effects of IABP has received much attention particularly in high- and low-risk coronary patients [12,13]. Even authors, who could not detect an increase in coronary flow, have reported an enhancement to myocardial perfusion with

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IABP [14]. The reduction of LV after-load as another well-known primary effect of IABP has been accounted for the improvement of LV oxygen demand and recovery of cardiac function. The improvement of ventricular systolic function with IABP is related to the fall in wall stress, particularly in the beats following balloon deflation [15].

Since the balloon inflates in diastole while the aortic valve is shut, there is lack of direct connection between balloon pumping and intra-cardiac events. However, we hypothesise that the positive effects of balloon counterpulsation on coronary flow may have changes in LV function, whose diastolic performance can improve consequently. In this paper, we examine this hypothesis and assess the effect of IABP on LV diastolic function, which in the setting of intensive care unit is usually studied from the filling pattern.

2. Materials and methods

We studied 20 patients with impaired LV function (end-diastolic dimension > 5.8 cm), aged 65 ± 7 years, 17 male, who had undergone cardiac surgery: coronary artery bypass grafting (CABG, $n = 13$), mitral valve repair (MR, $n = 3$), aortic valve replacement (AR, $n = 1$) or cardiac catheterisation ($n = 3$). Twelve patients had the IAB (Datascope, 8F, NJ, USA) inserted prior (average of 24 h) to the surgery and eight patients had the IAB inserted immediately after being anaesthetised to ensure LV support during surgery. None of the open-chest surgery patients ($n = 17$) had any difficulties weaning off the cardiopulmonary bypass and all patients continued using IABP (Datascope, XT 98, NJ, USA) after surgery to assist LV recovery. Balloons of 40 cm^3 were used in all patients except two who used 34 cm^3 balloons. The patients were studied in the intensive care unit less than 36 h after surgery, while under sedation, and a single cardiologist collected the data. The protocol of this study had been approved by the ethics committee of the Royal Brompton Hospital and written informed consent was obtained from all patients or their relatives prior to surgery.

Data were obtained at the end of 15 min of continuous IABP, at cycles of 1:1, 1:2, 1:3 and when the pump was on stand-by. A minimum of 5 min between recordings was allowed for haemodynamics to return to control condition. In order to eliminate time effects, the sequence of recording was varied between patients using a 4 by 4 Latin-square. Inflation and deflation timing were manually set for each patient at the beginning of the study, following the conventional settings; inflation started at the aortic dirotic notch and deflation during late diastole before the QRS wave of the ECG of the succeeding cycle.

We used pulsed Doppler transesophageal echocardiography (Hewlett Packard, Sonos 2500, Andover, USA) to study left anterior descending (LAD) coronary artery flow and transmitral flow velocities, and LV free-wall lengthening velocity. LAD flow velocities were measured from the

two-chamber view at 120° . Velocity time integral of diastolic coronary flow was calculated off-line at the end of the study. LV filling velocities were obtained from the four-chamber view with the sample volume placed by the tips of the mitral valve leaflets, from which LV filling E-wave peak velocity and time integral were determined.

LV free-wall movement was also studied using pulsed Doppler transesophageal echocardiography. Long axis movement was obtained from the four-chamber view with the M-mode cursor positioned at the LV free-wall; the images were zoomed to obtain a clear wall motion display. The early diastolic lengthening velocity of LV long axis was determined as the slope of the free-wall position against time in early diastole.

All Doppler and M-mode recordings were made photographically on paper at a speed of 10 cm/s with a superimposed electrocardiogram (ECG) and aortic pressure, which was measured at the tip of the balloon using the manometer attached to the balloon.

Haemodynamic values for IABP during 1:1, 1:2 and 1:3 are the mean of five consecutive assisted beats. These values were not compared to the unassisted beats of their respective pumping cycles (in 1:2 and 1:3), but rather to the mean value of five consecutive beats when the balloon was on stand-by.

2.1. Statistics

Patients served as their own controls; when the balloon was on stand-by and all comparisons in this paper were made using paired *t*-tests. In order to account for the multi comparisons, we used the Bonferroni-correction and *P* value $< 0.05/n$ was considered statistically significant, where *n* is the number of comparisons. The percent change between the augmented beat and the control was calculated as the ratio of the difference between the two values to that of control. The results are presented as mean \pm SD, and linear regression equations are presented.

3. Results

3.1. LAD coronary flow

The peak coronary diastolic flow velocity increased significantly with IABP 1:1 ($30 \pm 3\%$, $P < 0.001$), 1:2 ($22 \pm 2\%$, $P < 0.001$), and 1:3 ($17 \pm 2\%$, $P < 0.001$) compared to its value with the pump on stand-by. LAD velocity time integral followed a similar pattern and increased significantly with IABP 1:1 ($102 \pm 18\%$, $P < 0.001$), 1:2 (79 ± 15 , $P < 0.001$) and 1:3 ($67 \pm 10\%$, $P < 0.001$) compared to its value with the pump on stand-by. Fig. 1 shows a typical example of the LAD coronary velocity when IABP at 1:1 and when the pump was on stand-by. Mean values of peak LAD coronary flow velocity and its velocity time integral are presented in Table 1.

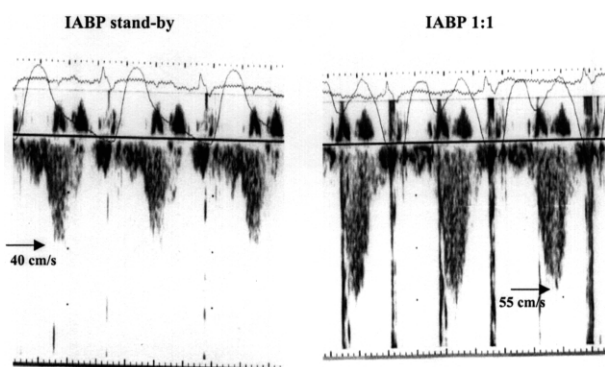


Fig. 1. LAD coronary flow velocity measured using pulsed Doppler echocardiography when IABP was on stand-by, left panel, and when at 1:1, right panel. The vertical ticks indicate flow velocity and each tick indicates 20 cm/s. The horizontal arrows indicate the peak LAD flow velocity, and ECG and aortic pressure are also shown for three consecutive beats. Mean LAD flow velocity time integral was 102% greater when the pump was at 1:1 than when the pump was on stand-by.

3.2. Mitral flow

The peak of LV early diastolic filling velocity E-wave increased with IABP 1:1 ($30 \pm 7\%$, $P < 0.001$), 1:2 ($20 \pm 6\%$, $P < 0.001$) and 1:3 ($11 \pm 4\%$, $P < 0.001$) compared to its value with the pump on stand-by. Mitral flow velocity time integral in early diastole E-wave also increased significantly during IABP 1:1 ($85 \pm 7\%$, $P < 0.001$), 1:2 ($75 \pm 6\%$, $P < 0.001$) and 1:3 ($60 \pm 4\%$, $P < 0.001$). Fig. 2 shows an example of mitral flow velocity at IABP 1:1 and when the pump was on stand-by. Mean values of peak LV filling E-wave velocity and its time integral are presented in Table 1.

3.3. Left ventricle wall movement

The LV long axis early diastolic lengthening velocity increased during IABP 1:1 ($29 \pm 4\%$, $P < 0.001$), 1:2

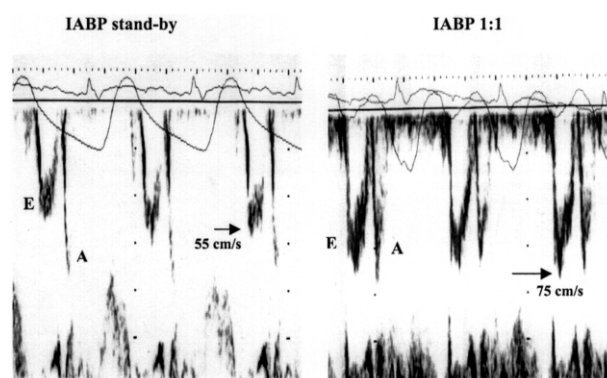


Fig. 2. Transmittal flow measured using pulsed Doppler echocardiography when IABP was on stand-by, left panel, and when at 1:1, right panel. The vertical ticks indicate flow velocity and each tick indicates 20 cm/s. The horizontal arrows indicate the peak E-wave, and ECG and aortic pressure are also shown for three consecutive beats. Mean E-wave velocity time integral was 85% greater when the pump was at 1:1 than when the pump was on stand-by.

($10 \pm 3\%$, $P < 0.001$) and 1:3 ($6 \pm 2\%$, $P < 0.001$) compared to its value when the pump was on stand-by. Fig. 3 shows an example of the long axis free-wall lengthening velocity when IABP at 1:1 and when the pump was on stand-by. Mean values of LV free-wall lengthening velocity are presented in Table 1.

3.4. Correlations and comparables

The increase in peak E-wave velocity correlated with the peak LAD coronary flow velocity at IABP 1:1 ($r = 0.74$, $P = 0.02$) as shown in Fig. 4a. Similarly, the increase in E-wave velocity time integral also correlated with LAD coronary velocity time integral at IABP 1:1 ($r = 0.70$, $P = 0.02$). The increase in LV free-wall early diastolic lengthening velocity correlated closely with the increase in peak E-wave velocity at IABP 1:1 ($r = 0.80$, $P < 0.001$) as shown in Fig. 4b.

Table 1
Effects of intra aortic balloon pump

		IABP cycles			
		1:1	1:2	1:3	Off
Peak LAD flow velocity (cm/s)	Mean \pm SD	50 \pm 7	47 \pm 5	45 \pm 6	39 \pm 7
	% Change	30 \pm 3	22 \pm 2	17 \pm 2	
LAD velocity time integral (cm)	Mean \pm SD	22 \pm 17	20 \pm 12	19 \pm 17	11 \pm 8
	% Change	102 \pm 18	79 \pm 15	67 \pm 10	
Peak mitral E-wave (cm/s)	Mean \pm SD	74 \pm 8	68 \pm 5	63 \pm 5	57 \pm 5
	% Change	30 \pm 7	20 \pm 6	11 \pm 4	
E-wave velocity time integral (cm)	Mean \pm SD	22 \pm 11	21 \pm 13	19 \pm 12	12 \pm 9
	% Change	85 \pm 7	75 \pm 6	60 \pm 4	
LV free-wall lengthening velocity	Mean \pm SD	6.5 \pm 2	5.5 \pm 2	5.3 \pm 1	5 \pm 1
	% Change	29 \pm 4	10 \pm 3	6 \pm 2	

Mean values of peak LAD flow and E-wave velocities, LAD and E-wave velocity time integrals and LV free-wall early diastole lengthening velocity at IABP cycles of 1:1, 1:2, 1:3 and when the pump was at stand-by. Note the progression of values with the pumping frequency. All parameters measured at IABP cycle 1:1 are significantly higher than those measured at 1:2 and 1:3, which suggests that IABP 1:1 is the most efficient pumping mode for patients post-cardiac surgery.

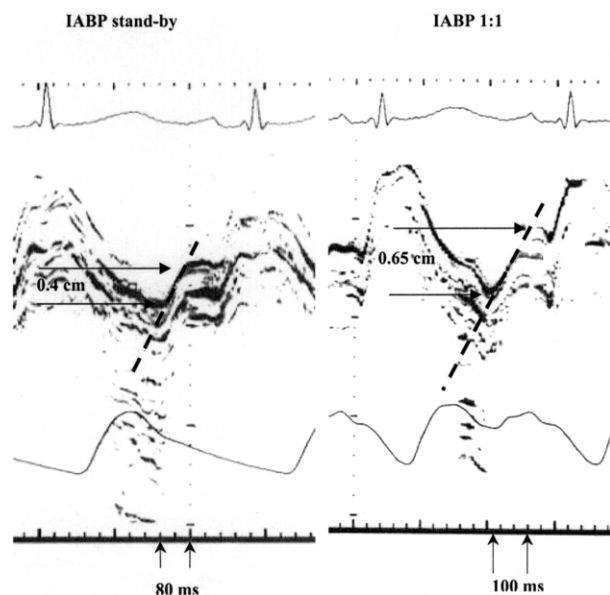


Fig. 3. M-mode of left ventricular free-wall when IABP was on stand-by, left panel, and when at 1:1, right panel. ECG and aortic pressure are superimposed in one cycle. The horizontal ticks at top and bottom of each panel indicate time and each tick indicates 40 ms. The vertical ticks indicate distance and each tick indicates 2 mm. The horizontal arrows indicate the distance covered by the free-wall at early diastole over the time that is indicated by the vertical arrows. LV free-wall early diastolic lengthening velocity is determined as the slope of the dashed line giving speeds of 5 and 6.5 cm/s during stand-by and IABP at 1:1, respectively.

The physiological parameters presented in Table 1 are compared between pumping cycles 1:1, 1:2 and 1:3. We found that all parameters are significantly higher at pumping cycles 1:1 than at 1:2 and 1:3 (all $P < 0.001$).

4. Discussion

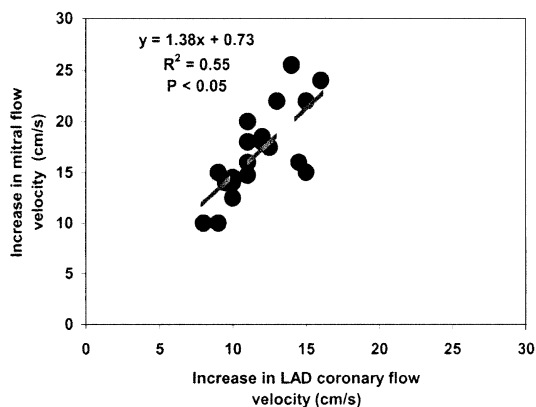
Intra-aortic balloon counter-pulsation does not augment cardiac output in the same way as a left ventricular assist device replaces the pumping function of the native LV. Instead, counter-pulsation provides direct assistance to LV in two ways: (a) it improves myocardial perfusion by augmenting coronary artery flow through increasing diastolic pressure in the ascending aorta and (b) it decreases myocardial oxygen consumption by reducing after-load [16]. In this paper, we present an evidence for indirect effect of the IABP on LV diastolic function as assessed by filling and wall motion velocities.

Conflicting data regarding the ability of IABP to increase coronary flow have been reported [16–19]. The most likely reason behind the controversy is mainly related to the different methods used for measuring coronary flow and the associated difficulty of the atherosclerotic narrowing of the diseased coronary arteries. It appears, however, that investigators are in agreement about the increase in coronary flow post-operatively, which is a finding that we can confirm from our data.

In post-cardiac surgery patients, intra-aortic balloon pump results in significant augmentation of LAD coronary peak diastolic flow velocities and velocity time integral. These increases were closely correlated with the respective increases in peak early diastolic LV filling velocities and velocity time integral. The increase in peak early LV filling velocities correlated with the increase in LV free-wall early diastolic lengthening velocity. These findings were consistent in all studied patients assuming wedge pressure remained unchanged, which although was not systematically recorded, we have no reason to believe that it can increase with IABP.

The increase of LV free-wall lengthening velocity is known to be a marker of myocardium recovery from ischemia post-cardiac surgery [20]. The increase in peak E-wave velocity correlated well with the increase in peak

a)



b)

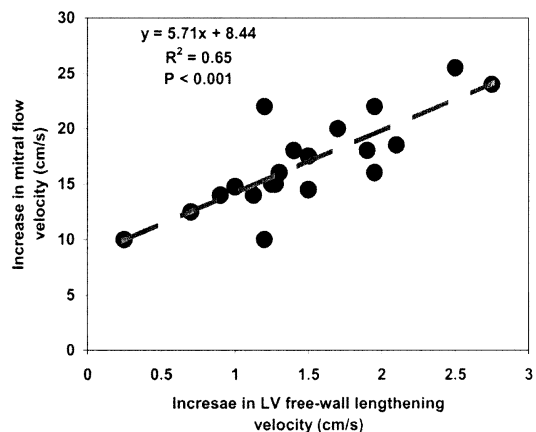


Fig. 4. The increase in peak early diastolic mitral flow velocity correlated with the increase in peak left anterior descending diastolic flow velocity (a), and with the increase in left ventricle free-wall lengthening velocity (b). The increase is taken as the difference between values with IABP 1:1 and when the pump was on stand-by.

LAD diastolic coronary flow velocity ($r = 0.74$) and with the increase in LV free-wall early diastolic lengthening velocity ($r = 0.80$) when the IABP at 1:1. We therefore reason that the increase in coronary flow during IABP released the myocardium from ischemia, increasing LV long axis lengthening velocity, which resulted in increased E-wave velocities and consequently enhanced ventricular filling.

It is clear from the data presented that there is a progression in the values of the parameters measured with the pumping cycles 1:3, 1:2 and 1:1. Although the mechanism behind this pattern requires separate investigation, pumping cycle 1:1 appears to be the mode of choice as it produces significantly the highest physiological values. Thus, IABP cycles 1:1 is expected to produce the best clinical results.

The mechanism of the increased LAD and LV early diastolic flow velocities during balloon pumping seems to be through the resulting increase in early diastolic lengthening velocity of the LV long axis. With acute coronary luminal obliteration and induction of ischemia, long axis amplitude and lengthening velocities drop [21]. Following successful opening of the artery, during angioplasty, long axis lengthening velocities increase [22]. Furthermore, changes in long axis lengthening velocities have been shown to determine the pattern of overall LV filling; reduced early diastolic velocities correlated with a compromised transmitral E-wave velocity, not only as part of the normal aging process [23] but also in patients with various ventricular disease [24,25]. These findings support the findings presented in this paper demonstrating close relationship between the changes in early diastolic long axis lengthening and LV filling velocities.

The effect of IABP on LAD coronary and mitral flow depends on a number of factors that could not be made constant in all patients. For example, the cross-sectional area ratio of the balloon to the aorta, heart rate and peripheral resistance are all patient specific parameters. Pharmacological agents such as inotropes and vasodilators were also inevitable clinical variables. However, none of these medications or others were changed between different assisting modes, supporting the conclusion that the alterations in the measured parameters reflect the intrinsic myocardial response to the effect of balloon pumping rather than the effect of the drugs. Measurements were also compared in the same patients at different events, supporting the sensitivity of the findings since the patients functioned as their own controls.

The results of this study indicate three clear clinical implications: (1) Using IABP in patients after cardiac surgery enhances both LAD coronary and early ventricular filling E-wave flows, thus enhancing diastolic cardiac function. (2) Although we recommend IABP cycles of 1:1 as the best mode of operation for assisting patients post-cardiac surgery, the weaning modes should be chosen selectively and dependently on the cardiac assistance required for each individual patient. (3) LV free-wall

movement and transmitral E-wave velocities in post-cardiac surgery patients can serve as markers for monitoring ventricular function indicating recovery of coronary circulation.

We conclude that the intra-aortic balloon pumping cycles 1:1 are proposed to be the most efficient mode of operation for post-cardiac surgery patients, whose LAD coronary flow increased significantly with IABP. This increase was associated with increased early diastolic LV free-wall lengthening velocities, which resulted in an increased early diastolic LV filling velocities. Although coronary flow is epicardial and mitral flow is intracardial, their close relationship, together with the increased left ventricle free-wall lengthening velocity suggest an improvement in the overall LV diastolic function with IABP.

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