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Intra-aortic Balloon Pumping: Does Posture Matter?

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Abstract: Background: The effect of the posture of semirecumbent patients on the hemodynamics and performance of intra-aortic balloon (IAB) were studied in vivo and in vitro. Methods: An IAB was inserted into a glass tube filled with saline, fully inflated and deflated using an intra-aortic balloon pump (IABP). Three successive cycles were filmed at 125 frames/s with the tube positioned at various angles between 0° (horizontal) and 90° (vertical). Pressure and flow were measured distal to both ends of the balloon. In parallel, coronary left anterior descending (LAD) flow velocity and aortic pressure were recorded in 6 patients using IABP, postcardiac surgery in the intensive care unit. Recordings were made when the patient was lying horizontally (recumbent) and when the patient's torso was inclined at 30° to the horizontal (semirecumbent). Results: With the tube horizontal, the inflation was effectively uniform along the length of the balloon. At all other angles, the higher end of the balloon inflated first, and mean pressure and flow measured distal to the higher end of the balloon were less than those measured at 0°. Mean aortic pressure and LAD flow decreased by $10 \pm 2\%$ ($P = 0.001$) and $15 \pm 3\%$ ($P = 0.001$), respectively, when the patient was semirecumbent compared to when the patient was recumbent. Conclusion: The decreased mean aortic pressure and LAD flow velocity suggests that unless patients using IABP are required to be semirecumbent, it may be best to position them horizontally to gain the full benefits of balloon counter pulsation to the coronary circulation. **Key Words:** Intra-aortic balloon pump—Posture—Hydrostatic pressure—Coronary flow.

The intra-aortic balloon pump (IABP) is the most widely used cardiac assist device in intensive care units and is commonly used before (1), during (2), and after (3) surgery for patients with left ventricular dysfunction. The balloon is inflated at early diastole, displacing blood along the aorta in both directions; toward the heart and toward the periphery. The amount of blood displaced toward the heart increases the pressure at the inlet of the coronary arteries and so enhances coronary flow (4). The balloon is deflated at late diastole, thus decreasing end diastolic aortic pressure, reducing afterload and consequently reducing left ventricular myocardium wall stress and oxygen demand (5).

The exact onset of inflation and deflation are patient- and pump-dependant (6), but in broad terms the balloon is desired to inflate as quickly as possible, as soon as the aortic valve shuts and remain inflated for the longest possible part of diastole. It is generally accepted that the longer the period during which the balloon is inflated the better the perfusion of the coronary arteries. The practice clinically is such that the onset of inflation is made to occur at the dicrotic notch of the aortic pressure pulse, while the onset of deflation is timed to occur just before the next upstroke of the aortic pulse (7).

Which part of the balloon inflates and deflates first during inflation and deflation, how the balloon moves during the cardiac cycle and what the relationship is between flow into the ascending and descending aorta during balloon inflation are questions that have not been clearly answered. Another question, more clinically relevant, concerns the effect of the posture of the patient on the hemodynamic parameters in the aorta during balloon counter-pulsation.

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Although an attempt to investigate the behavior of the balloon at different angles has been made (8), so far as the authors are aware these questions have not been clearly answered and addressing them is the main objective of this research.

If an IAB is immersed in a liquid-filled vessel with its long axis at an angle to the horizontal, the lower part of the balloon will be subjected to a higher hydrostatic pressure than is applied to the upper part of the balloon. Since the hydrostatic pressure in the helium within the balloon is virtually zero, this means that there will be a gradient in the transmural pressure along the long axis of the balloon. We therefore hypothesize that a hydrostatic pressure difference between the two ends of the balloon established by the posture of the patient would influence the pattern of inflation and deflation of the balloon, and thus affect its performance.

In order to investigate this, we carried out in vitro experiments in the laboratory and studied hemodynamic parameters in patients at different postures. In the laboratory experiments we established the mode of inflation and deflation of a balloon inserted into a glass tube at different angles to the horizontal. We also investigated the difference between values of pressure and flow distal to both ends of the balloon as a function of its inclination and pump frequency. In order to explore the effects of posture in practice, we studied the hemodynamic parameters in patients using IABP in the intensive care unit with the patients recumbent and semirecumbent.

MATERIALS AND METHODS

In vitro experiments

Experiment 1

A balloon, 27 cm long and 1.5 cm diameter when fully inflated (Datascope, 8F/40cc, Fairfield NJ, U.S.A.) was inserted into a 3 cm internal diameter glass tube filled with saline (0.9% sodium chloride). The balloon was fully inflated and deflated 20 times/min using an IABP (Datascope, 97 XT). The experiment was carried out with the tube at 0° (horizontal), 30°, 40°, 60°, and 90° (vertical). Three successive cycles were recorded at each angle using a high-speed video camera (Kodak, HG2000) at 125 frames/s. The frames were analyzed using slide-show software (IrfanView, Vienna, Austria) that presented the frames in sequence with an adjustable interval. We noted which part of the balloon inflates and deflates first by eye and determined the duration of inflation and deflation by multiplying the sampling rate (8 ms) by the number of frames that it took the balloon to fully inflate and fully deflate. Sequential frames were analyzed to determine the pattern and time of inflation and deflation. Since the balloon is flattened during the deflation part of the cycle, it was impossible to determine the local cross-sectional area of the balloon over much of the cycle. Instead, we measured the width of the projected image (in the horizontal direction) and used that information to determine when the balloon achieved full inflation. The pattern of inflation and deflation were noted and, when the pattern of opening was not uniform, the rate of propagation of the "wave of inflation" and "deflation" was measured.

Experiment 2

We repeated the above experiment with the balloon (Datascope, 8F/34cc) under a pressure within the physiological range (75 mm Hg). In this experiment pressure and flow were measured distal to both ends of the balloon. We ensured that the resistances to the flow from either end of the balloon was similar by making the apparatus symmetrical with respect to the tube length and fluid head in the case of the horizontal experiment. Four consecutive cycles were recorded at pumping rate of 1 : 1 at the horizontal position and at 30° to the horizontal. Heart rate of 100 beats per minute was mimicked using a specially designed system to regulate IABP inflation duration. Data were acquired using Labview (National Instruments, TX, U.S.A.) and analyzed using programs written in Matlab (The Mathworks, Natick, MA, U.S.A.). Peaks and mean pressure and flow were identified and determined for each set of data.

In vivo measurements

Six patients (5 males, 67 ± 5 years of age) were studied in intensive care unit postcoronary artery bypass surgery, whilst using IABP. The left anterior descending (LAD) coronary flow velocity was measured from the 2-chamber view at 120° using transoesophageal echocardiography (Hewlett Packard, Sonos 2500, Andover, MA, U.S.A.), and from which the velocity time integral of LAD diastolic coronary flow was calculated. Upper thoracic aortic pressure was measured using the fluid-filled pressure catheter at the tip of the balloon. This pressure signal was transferred and displayed on the echocardiogram, then printed and analyzed off-line. Heart rate was also measured and recorded using the IABP. Data were obtained in two groups, when the patient was lying horizontally and when the patient was inclined at approximately 30° to the horizontal. In each case data were collected over three breathing cycles at the end of 15 min of continuous intra-aortic balloon pumping at 1 : 1 and when the pump was on standby. Doppler recordings were made photographically on paper at a speed of 10 cm/s with a superimposed ECG and aortic pressure. All comparisons in this paper were made using the paired *t*-test and a value of $P < 0.05$ was considered statistically significant.

RESULTS

In vitro

Experiment 1

In the horizontal position, the inflation was effectively uniform along the length of the balloon and took 200 ms. The deflation was more complex and took approximately 280 ms; furling of the balloon at the end of deflation making the observation of time less certain. Figure 1 shows the balloon in the horizontal position during inflation and during deflation.

(a)

(b)

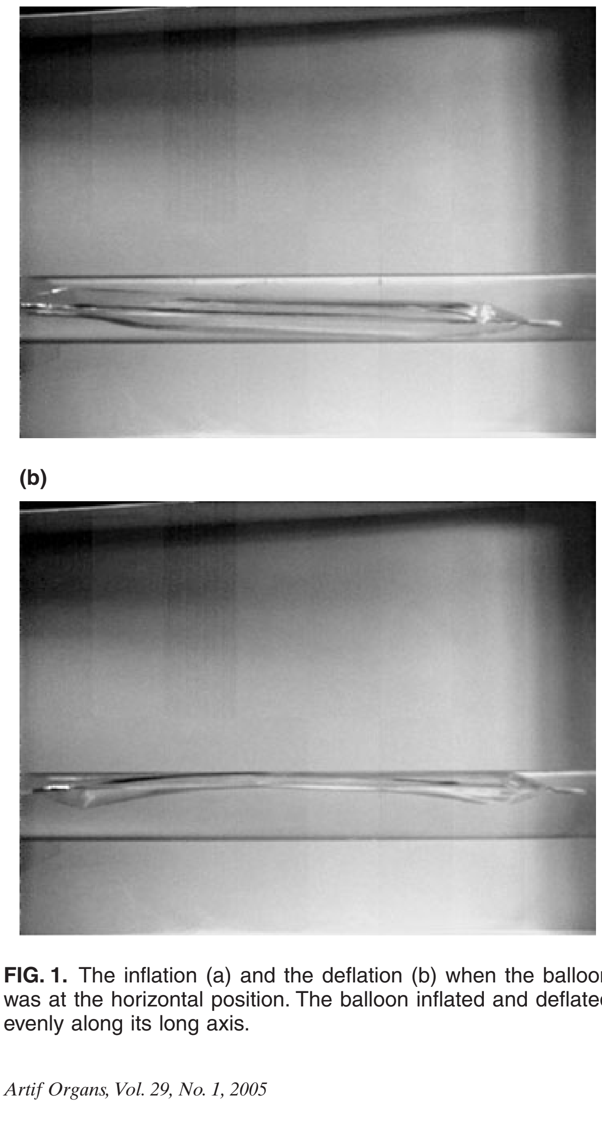

FIG. 1. The inflation (a) and the deflation (b) when the balloon was at the horizontal position. The balloon inflated and deflated evenly along its long axis.

(a)

(b)

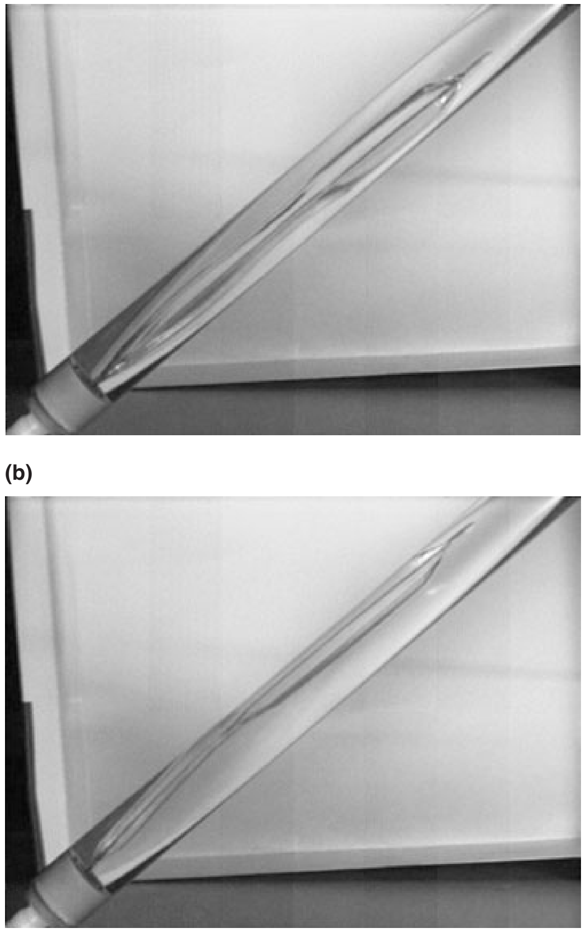

FIG. 2. The inflation (a) and the deflation (b) when the balloon was at 40° to the horizontal. The inflation started at the top of the balloon, which was subjected to a lower hydrostatic pressure than the lower part of the balloon. The deflation, in contrast, started at the bottom of the balloon.

At all other angles, the modes of inflation and deflation were distinctively different from those observed at 0°.

At 60° with a hydrostatic pressure difference of 17 mm Hg between the two ends of the balloon, the top of the balloon inflated first and a wave of inflation ran down the balloon with a speed of 1.7 m/s inflating it in 160 ms. On deflation, the bottom of the balloon deflated first and a wave of deflation ran up the balloon with a speed of 0.95 m/s, emptying it in 280 ms. These results were similar to those found at all other angles and independent of whether the balloon was inserted from the top or bottom of the tube. The illustration in Fig. 2 is for a balloon at 40° to the horizontal. It should be noted that as inflation proceeds buoyancy moves the balloon upwards and this motion reverses on deflation.

TABLE 1. *Hemodynamic parameters measured in vitro distal to both ends of the balloon at 0° and at 30°*

	Balloon horizontal		Balloon at 30°	
	Lower end	Upper end	Lower end	Upper end
V_0 (cm^3)	0	0	0	0
V (cm^3)	20	20	24	16
P_0 (mm Hg)	75	75	75	64
P (mm Hg)	85	85	90	68
U_0 (cm/s)	0	0	0	0
U (cm/s)	2.8	2.8	3.4	2.3

V, P, and U denote mean volume, pressure, and velocity, respectively, resulting from the inflation of the balloon. Subscript 0 denotes initial condition before balloon inflation.

Experiment 2

In the experiment where the balloon was subjected to pressure in the physiological range, when the balloon was at the horizontal position, volumes displaced, mean pressure, and velocity were observed to be equal upstream and downstream from the balloon. When the balloon was at an angle to the horizontal the volume of fluid displaced, mean pressure, and velocity at the higher end of the balloon were less than values when the balloon was at the horizontal position and less than those of the lower end of the balloon. The decrease of hemodynamics values at the upper end of the balloon was associated with an increase of those at the lower end of the balloon. Table 1 includes all the values at both positions.

In vivo

Results obtained in the intensive care unit confirmed those found in the laboratory. Thus, when the patients were semirecumbent at 30° to the horizontal, mean aortic pressure and mean LAD flow velocity decreased by 10 ± 2% (80.4 ± 14 vs. 88.4 ± 11 mm Hg, $P < 0.05$) and 15 ± 3% (55 ± 4 vs. 65 ± 5 cm/s, $P < 0.05$), respectively, compared with when the patient was at 0°. Also, LAD velocity time integral (VTI) was lower by 15% (11 ± 2 vs. 13 ± 2 cm/s, $P < 0.05$) than when the patients were recumbent. No change in heart rate was observed.

DISCUSSION

The flow of blood induced by the inflation and deflation of the balloon in vivo is undoubtedly very complex. It is affected by several parameters such as the local mechanical properties of the aortic wall, the impedance of the circulation both upstream and downstream of the balloon, and the reflected waves arriving at the various segments of the aorta at different times. With this in mind, the in vitro experiments in rigid tubes with nonphysiological artificial conditions at the ends of the tube should be thought of as experiments to establish possibilities rather than realistic modelling experiments. The principle result is that the inflation and deflation patterns of the balloon are dependent, at least in part, upon the hydrostatic pressure gradient between the two ends of the balloon. Given these differences, it is not surprising that the flow produced by the balloon was also changed with the angle of the tube to the horizontal.

If an IAB is inclined to the horizontal, the hydrostatic pressure difference between the two ends of the balloon plays an important role in determining the mode of inflation and deflation as demonstrated in experiment 1. This also affects the total inflation and deflation times because different parts of the balloon are subjected to different pressures. We therefore postulate that these changes in inflation and deflation times may affect the optimum triggering times depending upon the posture of the patient, and therefore these times need to be readjusted when the posture of the patient changes.

The time it takes the pump to fully inflate and deflate the balloon in a typical patient, could well disagree with the results of experiment 1. A possible explanation for this discrepancy is that the experiment was carried out at a mean pressure well below the physiological range. In addition, it is accepted that the inflation and the deflation of the balloon depend in the largest part on the transmural pressure between blood pressure in the aorta and gas pressure inside the balloon. The higher the transmural pressure the faster the inflation and slower the deflation, which are our findings. For example, when a patient changes from recumbent to semirecumbent position, balloon inflation may occur in a shorter time, and if the duration of inflation is unchanged, a premature onset of deflation can occur. We suggest therefore, that inflation and deflation timings should be closely monitored and adjusted according to each patient's aortic pressure.

In the in vitro experiment 1, we observed that the balloon moves, respectively, upwards and downwards during the inflation and deflation periods. The balloon floats upwards (parallel to its long axis) as it is being filled until it touches the upper wall of the tube then it moves downwards until it touches the lower side of the tube as it is being deflated. A possible cause for these movements is the force of buoyancy since the density of helium is so much less than saline and the composite from which the balloon is made is heavier than saline.

Other researchers have also noted the balloon movement in the aorta of man (9) and it has been suggested that this behavior is one of the reasons for rupture in the membrane of the balloon, as it rubs against plaques in an atherosclerotic aorta (10).

In the in vitro experiment 2, when the balloon was horizontal, the pressure and flow measured at the two ends of the balloon were similar, indicating that during inflation the balloon displaces half of its volume upstream and the other half downstream. However, when the balloon was inclined at 30° the ratio of volume displacement changed; more fluid was displaced and pressure increased downwards than was observed when the balloon was at the horizontal position. These increases distal to the lower end of the balloon were associated with decreases in the pressure and flow distal to the upper end of the balloon. These observations may be explained by the results of experiment 1. When the balloon is at an angle to the horizontal, during inflation its top end starts to fill first, displacing fluid downwards.

Similarly in patients, the hydrostatic pressure difference between the upper and lower ends of the balloon affects the direction in which the distribution of the volume is displaced by the balloon. The results of this research based primarily on the hydrostatic effects, demonstrate that a decrease in the aortic mean pressure and a consequent decrease in coronary flow velocity is to be expected if the patient is positioned at an angle to the horizontal, compared to those values when the patient is positioned horizontally.

Patients' aortic flow velocity has also been measured in the intensive care unit when the patients were positioned at the horizontal level and when they were semirecumbent, using Doppler echocardiography. While systolic measurements were of good quality, diastolic measurements were noisy and almost unreadable due to ambiguity in Doppler measurements of small amplitude flows such as occur during diastole. Measurement of flow in the ascending aorta and the femoral artery during diastole needs further investigations, probably intraoperatively using flow probes that can be placed around the ascending aorta.

CONCLUSION

Any hydrostatic pressure difference between the two ends of the IAB influences its mode of operation. A decreased mean aortic pressure and LAD coronary flow when the balloon is at an angle to the horizontal suggests that unless patients using IABP are required to be semirecumbent, it may be best to position them in a horizontal position to gain the full benefits of balloon counterpulsation to the coronary circulation.

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