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Maximizing the Hemodynamic Benefit of Enhanced External Counterpulsation

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Summary

Background: Enhanced external counterpulsation (EECP) has been demonstrated to be an effective treatment for angina and exertional ischemia in patients with coronary disease.

Hypothesis: It is hypothesized that the ability of EECP to enhance the recruitment or development of coronary collaterals in coronary artery disease may be determined by the relative magnitude of diastolic augmentation (DA) and systolic unloading (SU). This study examines the relation between the proposed EECP effectiveness ratio (DA/SU), as assessed by finger plethysmography, and changes in descending aortic flow as assessed by Doppler echocardiography in 15 patients during EECP.

Methods: Varying external cuff pressures (0–275 mmHg) were used to generate a range of DA/SU ratios. The effect on aortic antegrade systolic and retrograde diastolic flow was assessed by Doppler echocardiography to determine whether there was an optimal EECP effectiveness ratio that maximizes the hemodynamic effects of EECP. With increasing DA/SU there was an initial positive linear increase in both systolic and diastolic flow volume. Systolic flow maximized at an effectiveness ratio of 1.5 and diastolic flow at a ratio of 2.0.

Result: Therefore, effectiveness ratios (DA/SU) in the range of 1.5–2.0 are optimal for maximizing the hemodynamic effects of EECP.

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Introduction

Enhanced external counterpulsation (EECP) is a noninvasive technique of aortic counterpulsation that provides benefits of decreased anginal frequency,[1,2] improved exercise tolerance,[2] and improved stress myocardial perfusion[1,3] in patients with chronic angina. It applies external pressure in synchronization with the cardiac cycle to three sets of cuffs wrapped around the lower extremities. The cuffs are sequentially inflated at the onset of diastole, producing aortic counterpulsation (retrograde aortic blood flow) and also increasing venous return. The retrograde aortic blood flow increases diastolic blood volume and pressure [diastolic augmentation (DA)] in the aorta. The external pressure in all three sets of cuffs is released at the onset of systole, decreasing afterload [systolic unloading (SU)] and resulting in an increase in cardiac output with a lowered systolic pressure. The EECP device is shown in Figure 1. Samples of the finger plethysmographic waveform obtained during rest and during EECP illustrating DA and SU are shown in Figure 2.

It has been hypothesized that the sustained benefits of EECP in patients with coronary artery disease result from effective DA which in turn increases perfusion pressure and volume in the coronary bed, thereby promoting collateral formation or recruitment.[4–7] By decreasing afterload during cardiac systole, EECP acutely reduces cardiac work load, wall stress, and myocardial oxygen consumption while increasing the cardiac output. The systolic unloading effects may also have longer-term importance for neurohumoral regulation and ventricular remodeling. It is rational to postulate that the acute hemodynamic effectiveness of EECP is proportional to its ability to increase DA and decrease afterload, that is, SU, and that this may be simply expressed as a ratio of diastolic augmentation to systolic unloading (DA/SU or the EECP effectiveness ratio).

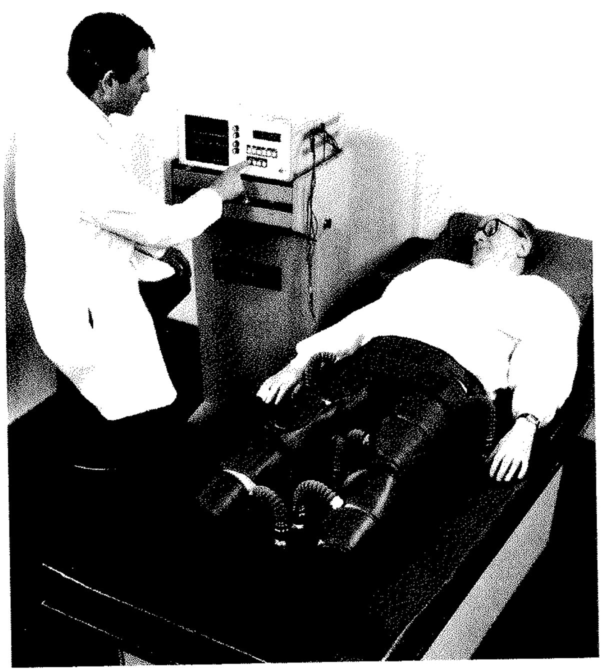

FIG. 1 The enhanced external counterpulsation (EECP) consists of a control console, a bed with three sets of inflation/deflation valves, three pairs of cuffs wrapped around the lower extremities, and a compressor unit (not shown).

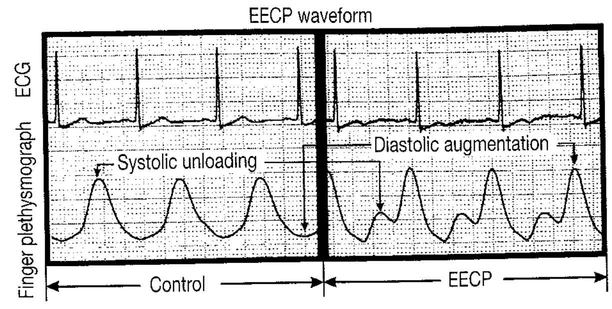

FIG. 2 Waveform obtained by finger plethysmography at rest and during enhanced external counterpulsation (EECP) treatment. Systolic unloading is the reduction of the peak systolic amplitude, diastolic augmentation is the increase of peak diastolic amplitude. ECG = electrocardiogram.

This study was undertaken (1) to assess the relation between the EECP effectiveness ratio (DA/SU) as measured by finger plethysmography and changes in systolic and diastolic descending aortic flow at rest and during EECP,[8] and (2) to determine whether there is an optimal DA/SU range that would maximize antegrade systolic and retrograde augmented diastolic aortic flow. Though usually well tolerated, the most frequently observed side effects of EECP treatment are related to barotrauma and local bruising. The current EECP device can generate external cuff pressures as high as 275 to 300 mmHg. An optimal DA/SU ratio may not require maximizing the external cuff pressure. Identifying the optimal range would potentially allow the use of lower cuff pressures capable of producing effective hemodynamic changes with less risk of barotrauma.

Methods

This study has been approved by the Institutional Review Board on research involving humans and has been carried out in accordance with the Declaration of Helsinki. Seventeen subjects undergoing EECP were considered for entry. In all, 15 men and 2 women with a mean age of 53.7 ± 10.0 years were enrolled. Two patients were excluded after screening because of inadequate windows for two-dimensional (2-D) and pulsed Doppler echocardiography of the descending aorta from the suprasternal notch. The 15 subjects studied were positioned supine on the EECP bed with appropriately applied EECP cuffs. With 2-D guided pulsed Doppler echocardiography, measurements of systolic and diastolic flow in the proximal descending aorta at rest and during EECP were made at a fixed depth from the suprasternal notch using a Hewlett-Packard (Andover, Mass., USA) Sonos 1500 machine and a 2.7 MHz probe. Patients underwent counterpulsation for 5 min at each incremental level of externally applied pressure, producing an appropriate increase in the effectiveness ratio. Doppler data were obtained for each increment in the effectiveness ratio after 5 min of sustained external counterpulsation at that level.

Enhanced external counterpulsation cuff pressure was incrementally adjusted over a range of 100–275 mmHg. At each level of cuff pressure, the EECP effectiveness ratio (DA/SU) was calculated from the arterial pressure waveform obtained using the finger plethysmogram, as shown in Figure 3. The EECP effectiveness ratio was calculated as the ratio of the

$$\text{EECP effectiveness ratio} = \frac{\text{Peak diastolic amplitude}}{\text{Peak systolic amplitude}}$$

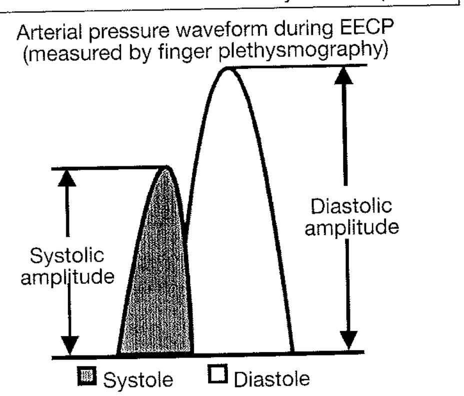

FIG. 3 The enhanced external counterpulsation (EECP) effectiveness ratio is calculated from the waveform obtained by finger plethysmography. Note that the reference zero (baseline) used in this calculation is at the point of end diastole.

peak diastolic amplitude divided by the peak systolic amplitude averaged over five cardiac cycles.

Pulsed Doppler echocardiography of systolic and diastolic descending aortic blood flow was performed at each level of incremental cuff pressure. Systolic and diastolic time velocity integrals (STVI, DTVI) and the heart rate (HR) were recorded at each level of the EECP effectiveness ratio. The product of STVI (stroke distance) and the HR for each increment of DA/SU during EECP minus this product at rest (baseline) and divided by the patient's baseline value was used to estimate the percentage increase in cardiac output (% increase CO) produced by that level of DA/SU. The DTVI was recorded for each level of the ratio DA/SU. The averaged (5 consecutive cardiac cycles) results of DTVI and (STVI × HR) were plotted against the effectiveness ratio (DA/SU). The effect of increasing DA/SU on the descending aortic (DTVI/STVI) was also plotted. Individual data points were plotted in a scattergram fashion. To aid in the visual interpretation, curves were fitted to the data points using a least squares regression method with second order polynomial curve fit.

Subjects were excluded from this study for lack of an echocardiographic window as well as for the usual exclusion criteria including decompensated heart failure, unstable angina or myocardial infarction within 3 months, aortic insufficiency, severe peripheral arterial disease or venous thrombophlebitis, arrhythmias interfering with timing of counterpulsation (frequent ectopy, atrial fibrillation, pacemaker), uncontrolled hypertension (blood pressure > 180/110), and bleeding diathesis.

Results

Fifteen subjects (14 men, 1 woman) with a mean age of 54 years (range 38–66 years) were entered into this study. The EECP was well tolerated by all subjects and there were no adverse effects.

The results of increases in the EECP effectiveness ratio (DA/SU) on changes in DTVI and cardiac output (STVI × HR) with EECP are illustrated in Figures 4 and 5. The EECP effectiveness ratio (DA/SU) obtained by progressively increasing external cuff pressure from 0 to 275 mmHg ranged from 0 to 2.6. As assessed by STVI × HR, CO at first rose in a linear fashion with an increasing (DA /SU) ratio before plateauing at about 60–70% above baseline, around an EECP effectiveness ratio (DA/SU) of 1.5. Similarly, DTVI rose in a linear fashion with increasing DA/SU before plateauing around a ratio of 2.0. The relative ratio of retrograde diastolic blood volume/antegrade systolic blood volume (DTVI/STVI ratio) also rose in a linear fashion from a baseline average of 9% to an average of about 50% before plateauing at an EECP effectiveness ratio (DA/SU) of about 2.0, as shown in Figure 6.

Discussion

Successful aortic counterpulsation is reflected by an augmented diastolic and a decreased systolic aortic pressure. The hemodynamic effects of diastolic augmentation and systolic unloading with the intra-aortic balloon pump (IABP) are assessed invasively through the balloon catheter lumen (central aortic pressure) or a radial arterial line. The present study used finger plethysmography as a noninvasive means for optimizing the hemodynamic effects of EECP. It is hypothesized that increasing external cuff pressure would increase the EECP effectiveness ratio. This effect was observed in the present study.

Doppler echocardiography has previously been used to demonstrate and semiquantify the hemodynamics of EECP.[8] The current study examines the effect of higher EECP cuff

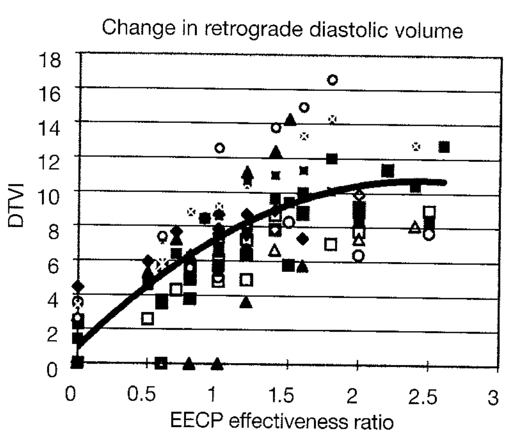

FIG. 4 Diastolic time velocity integral (DTVI) as assessed by pulsed Doppler echocardiography of the descending aorta. Counterpulsation produces retrograde aortic flow and diastolic augmentation. The curve is generated by the least squares regression method using a second order polynomial curve fit. EECP = enhanced external counterpulsation.

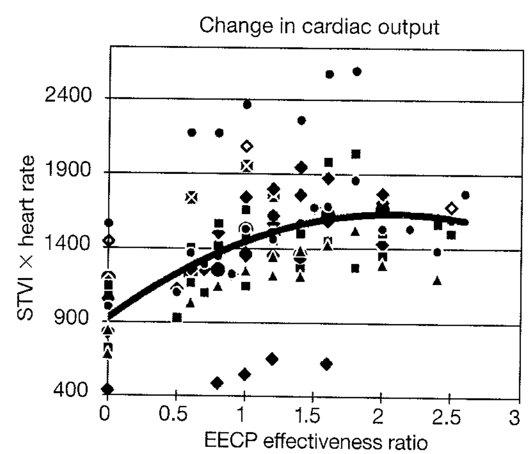

FIG. 5 The percent increase in cardiac output [systolic time velocity integral (STVI) × heart rate) as assessed by pulsed Doppler echocardiography of the descending aorta. Counterpulsation produces systolic unloading and an increase cardiac output. The curve is generated by the least squares regression method using a fourth order polynomial curve fit.

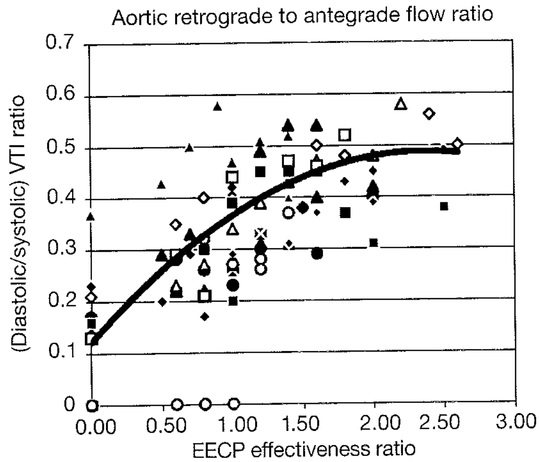

FIG. 6 The ratio of retrograde and antegrade aortic flow (DTVI/STVI) during EECP as assessed by pulsed Doppler echocardiography of the descending aorta. Counterpulsation disproportionately increases retrograde diastolic flow over antegrade systolic flow. DTVI/STVI = diastolic/systolic velocity time integral, EECP = enhanced external counterpulsation.

pressures on increasing aortic blood flow using Doppler echocardiography. Higher cuff pressures may predispose patients to barotrauma to the skin and muscle. The effectiveness ratio where plateauing occurs is difficult to identify precisely and is best characterized by a range of values. The present study shows that there may not be any additional substantial hemodynamic advantages in attempting to augment diastolic flow and cardiac output once an EECP effectiveness ratio (DA/SU) in the range of 1.5 to 2.0 has been achieved. Increasing EECP cuff pressure to the optimal level of DA/SU will achieve maximal hemodynamic benefit and minimize patient discomfort and the potential for barotrauma. These results need to be further validated by invasive hemodynamic studies.

Limitations

Traditionally, calculation of cardiac output using Doppler techniques has used measurements from the left ventricular outflow tract. This is technically difficult in patients undergoing EECP due to their being in supine position and the difficulty of achieving steady precordial transducer position due to motion artifact from EECP cuff inflation and deflation. The use of the suprasternal window gives better transducer stability while offering imaging of the ascending and descending aorta for measurement of hemodynamic parameters during EECP. The major limitation of using the suprasternal notch for Doppler interrogation is the difficulty in accurately assessing aortic diameter by 2-D echocardiography because the beam is parallel to the imaged aortic walls. Good images from the suprasternal notch were obtained in 15 of 17 subjects screened, demonstrating its utility in providing a noninvasive method of evaluating EECP augmentation.

The measured changes in time velocity integrals accurately reflect changes in volume only if the cross sectional area at the site of pulsed Doppler sampling is constant. Since EECP causes both systolic unloading and diastolic augmentation, it alters the distending forces on the aorta, and hence the aortic cross-sectional area, to a degree determined by aortic elastic compliance. The decrease in aortic pressure at the onset of systole will tend to decrease the aortic cross-sectional area and lead to an overestimate of the increases in CO as estimated by STVI × HR. Conversely, the increase during diastole of pressure and volume in the descending aorta will increase the cross-sectional area. The change in DTVI will therefore underestimate the true increase in diastolic volume, because it represents a stroke distance uncorrected for the increased diastolic aortic cross-sectional area. Since diastolic volume changes are underestimated and systolic volume changes are overestimated, the ratio of DTVI/STVI will also underestimate the relative change in the ratio of aortic diastolic volume versus systolic volume during EECP. The small changes in aortic cross-sectional area cannot be assessed accurately by this technique because of movement artefact and due to the fact that the echo beam is parallel to the walls of the aorta.

The variability in individual response to changes in DA/SU ratio by increasing externally applied cuff pressure during EECP resulted in some subjects not being able to attain higher DA/SU ratios (range 1.2–2.0) despite maximal cuff pressures. As a result, the standard error of the mean becomes wider for higher EECP effectiveness ratios, and the plotted curves are therefore less reliable at higher ratios. Decreasing the confidence interval would require confirmation with a greater number of subjects.

Higher cuff pressures are demonstrated to result in greater diastolic augmentation and an increase in the hemodynamically assessed effectiveness ratio. The relation of augmentation to clinical improvement is not clear. It is not known whether a minimum level of effective augmentation is required for the clinical response of anginal improvement and improved myocardial perfusion. It is also unknown whether greater degrees of augmentation result in further improvements in response (earlier or more complete).

Conclusions

This study demonstrates that EECP produces significant diastolic augmentation and systolic unloading. It defines an effectiveness ratio which can be measured by finger plethysmography to quantify the hemodynamic effect of EECP noninvasively. The following conclusions can be drawn from our results:

(1) EECP has marked effects on the magnitude of diastolic retrograde and systolic antegrade blood flow in the descending aorta; (2) the hemodynamic effects of diastolic augmentation and systolic unloading are dependent on the magnitude of the applied external pressure; (3) there is a positive linear relation between the noninvasively assessed EECP effectiveness ratio and cardiac output, the diastolic time velocity integral, and the

diastolic to systolic time velocity integral ratio in the descending aorta; and (4) an EECP effectiveness ratio that ranges from 1.5 to 2.0 maximizes the hemodynamic effects of EECP and minimizes the possibility of cuff barotrauma.

References

1. Lawson WE, Hui JCK, Soroff HS, Zheng ZS, Kayden DS, Sasvary D, Atkins H, Cohn PF: Efficacy of enhanced external counterpulsation in the treatment of angina pectoris. *Am J Cardiol* 1992; 70:859–862
2. Lawson WE, Hui JCK, Zheng ZS, Burger L, Jiang L, Lillis O, Oster Z, Soroff H, Cohn PF: Improved exercise tolerance following enhanced external counterpulsation: Cardiac or peripheral effect? *Cardiology* 1996;87:1–5
3. Lawson WE, Hui JCK, Zheng ZS, Oster Z, Katz JP, Diggs P, Burger L, Cohn CD, Soroff HS, Cohn PF: Three-year sustained benefit from enhanced external counterpulsation in chronic angina pectoris. *Am J Cardiol* 1995;75:840–841
4. Lawson WE, Hui J, Burger L, Cohn PF: Five year follow-up of morbidity and mortality in 33 angina patients treated with enhanced external counterpulsation. *J Invest Med* 1997;45:212A
5. Lawson WE, Hui JCK, Zheng ZS, Burger L, Jiang L, Lillis O, Soroff HS, Cohn PF: Can angiographic findings predict which coronary patients will benefit from enhanced external counterpulsation? *Am J Cardiol* 1996;77:1107–1109
6. Kern MJ, Aguirre FV, Tatineni S, Penick D, Serota H, Donohue T, Salter K: Enhanced coronary blood flow velocity during intra-aortic balloon counterpulsation in critically ill patients. *J Am Coll Cardiol* 1993;21:359–368
7. Kern MJ, Aguirre F, Bach R, Conohue T, Siegel R, Segal J: Augmentation of coronary blood flow by intra-aortic blood flow by intra-aortic balloon pumping in patients after coronary angioplasty. *Circulation* 1993;87:500–511
8. Suresh K, Simandl S, Lawson WE, Hui JCK, Guo T, Burger L, Soroff H, Cohn PF: Acute hemodynamic benefit of enhanced external counterpulsation. *J Am Coll Cardiol* 1996;27:22A