Pulsatile mode of operation of left ventricular assist devices and pulmonary haemodynamics

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Abstract

OBJECTIVES: To determine the effect of differing modes of left ventricular assist device (LVAD) operation: synchronous, independent (asynchronous or pseudosynchronous) or counter pulsation (antisynchronous), on left atrial pressure, pulmonary artery pressure, pulmonary blood flow and right ventricular work load, utilizing a previously published electrical analogy of the systemic and pulmonary circulation and the heart.

METHODS: A previously published electrical analogy of the systemic and pulmonary circulation was utilized. The Simulation Package with Integrated Circuit Emphasis (LTSPICE IV) was utilized. Three LVAD operation mode scenarios were analysed: synchronous, counter pulsation and independent pulsatile. The root mean square of the pulmonary artery pressure (PAP), left atrial pressure (LAP) and pulmonary blood flow (PBF) were calculated, as was the right ventricular work load.

RESULTS: Counter pulsation LVAD operation resulted in the lowest LAP, PAP, right ventricular work load and the highest pulmonary blood flow. Independent pulsation resulted in the highest LAP, PAP and the lowest pulmonary blood flow. This technique actually increased RV work load.

CONCLUSIONS: If an LVAD is to be operated in a pulsatile mode, the counter pulsation mode reduces pulmonary artery and left atrial pressure and increases pulmonary blood flow and thus cardiac output. This is in addition to the reduced right ventricular energetic requirement, a finding previously described. Clinical validation of our findings is necessary.

Keywords: Left ventricular assist device • Electrical analogy • Simulation

INTRODUCTION

Left ventricular assist devices (LVADs) are utilized for failing left ventricle function [1, 2]. LVADs can operate in a number of different modes: continuous or pulsatile mode; the latter can be independent, synchronous or counter pulsation with respect to the native heart.

LVADs work in a manner analogous to intra-aortic balloon pumps increasing forward flow and decreasing the work of the left ventricle [3].

The left and right ventricles contract essentially simultaneously. This results in the pulmonary and aortic valves being open simultaneously and the mitral and tricuspid valves being closed simultaneously. As the mitral valve is closed when the right ventricle contracts, right ventricular stroke volume has to be accommodated by the pulmonary vasculature [4]. The rise in pulmonary artery pressure depends on the native pulmonary vascular compliance. If the mitral valve was open when the right ventricle contracts or the LVAD is filling during right ventricle systole, then the left atrial pressure will be lower and the forward flow higher, i.e. counter pulsation.

Previous work has identified that operating an LVAD in a counter pulsation manner results in reduced left ventricular work [5]. We extend this analysis by analysing the differing modes of LVAD operation: synchronous, independent or counter pulsation (antisynchronous), on pulmonary artery pressure and flow utilizing a previously published electrical analogy of the systemic and pulmonary circulation and the heart [6].

METHODS

The previously published electrical analogy of the systemic and pulmonary circulation was utilized [6], Fig. 1. The Simulation Package with Integrated Circuit Emphasis (SPICE) circuit listing is detailed in the Supplementary material.

Three LVAD operation mode scenarios were analysed: synchronous, counter pulsation (antisynchronous) and independent pulsatile (pseudosynchronous or asynchronous).

Baseline variables for model

Systemic blood pressure of 140 mmHg, a cardiac output of 5.5 l/min. It was assumed that 1 V = 1 mmHg of pressure. The intrinsic heart rate was assumed to be 60 beats/min for all analyses, and 1 mA = 1 l/min. The root mean square of the pulmonary artery pressure (PAP), left atrial pressure (LAP) and pulmonary blood flow (PBF)
were calculated utilizing LTSPICE (CTRL and left click on the variable to be measured). Simulation assumed no aortic regurgitation and the absence of a patent foramen ovale.

Incorporation of left ventricular assist device into circulatory model

The different modes of operation of the LVAD were simulated by adjusting the mode of operation of the voltage source, labeled as left ventricle in Fig. 1. For the settings of the voltage source shown in Fig. 1, for synchronous operation was DC offset (V) 0, amplitude (V) 120, frequency (Hz) 1.00 and delay (s) 0.0, counter pulsation operation was DC offset (V) 0, amplitude (V) 120, frequency (Hz) 1.00 and delay (s) 0.5, and asynchronous operation was achieved via two different frequency voltage sources, DC offset (V) 0, amplitude (V) 120, frequency (Hz) 1.00 and delay (s) 0.0, and DC offset (V) 0, amplitude (V) 120, frequency (Hz) 0.75 and delay (s) 0.0—equivalent to a native ventricular rate of 45/s and an LVAD rate of 60.

Right ventricular work load

The right ventricular work load was calculated form the cardiac output multiplied by the root mean square PAP. The results were normalized (referenced) to the baseline function of the RV in a normally functioning heart.

Effect of heart rate

The effect of varying the native heart rate from 30 to 120 beats/min was investigated. For asynchronous operation, the native heart rate was kept at 60/min and the LVAD rate was varied.

Software

LTSPICE IV (www.linear.com) was utilized for circuit simulation. The oscilloscope function was utilized to read blood pressure—aortic, LAP and PAP (voltage) and pulmonary blood flow (current) values from the simulated circuit.

RESULTS

Baseline

The baseline output of the model for comparison purposes is shown in Fig. 2.
Counter pulsation

The effect of counter pulsation LVAD operation on LAP and PBF is shown in Fig. 3. It should be noted that the aortic trace is 180° out of phase compared with Fig. 2, which is due to the technique counter pulsation.

Asynchronous

The effect of asynchronous LVAD function on pulmonary blood flow and left atrial pressure is shown in Fig. 4. It can be seen that asynchrony causes highly variable differences in LAP and pulmonary blood flow.

Synchronous

The effect of synchronous LVAD operation on LAP and PBF is shown in Fig. 5.

Comparative analysis

The effect of differing LVAD pulsatile support strategies on LAP, PAP and PBF is shown in Fig. 6. It can readily be seen that asynchronous operation is associated with a higher pulmonary artery pressure, increased LAP and reduced PBF. Counter pulsation results in the lowest PAP, LAP and the greatest PBF. The increase in cardiac output possible with counter pulsation assumes the right ventricle to be unlimited in its function and the pulmonary compliance to be normal, a situation that is uncommon in clinical practice.

Right ventricular work load

The normalized RV work load for the differing LVAD pulsatile support strategies is shown in Fig. 7. It can be seen that the counter pulsation technique has the lowest RV work load (84%), and the asynchronous mode has the highest (118%, which indicated that the technique actually increases RV work load), compared with a normal RV (100%).

Effect of heart rate

The effect of heart rate on left atrial pressure is shown in Fig. 8. It can be seen that regardless of heart rate, the counter pulsation mode is associated with a lower left atrial pressure. A lower left atrial pressure results in a reduced pulmonary artery pressure and/or increases pulmonary blood flow (data not shown).

Figure 3: The effect of counter pulsation left ventricular assist device function on aortic, pulmonary artery and left atrium pressure traces and pulmonary blood flow.

Figure 4: The effect of asynchronous left ventricular assist device operation on aortic, pulmonary artery, left atrium pressure traces and pulmonary blood flow.

Figure 5: The effect of synchronous left ventricular assist device function on aortic, pulmonary artery, left atrium pressure traces and pulmonary blood flow.
 LVADs providing continuous flow is the most common mode of operation [14]. Continuous flow from an electrical analogy would provide the lowest left atrial and pulmonary artery pressures. An electrical model is unable to assess the merits and detrimental effects of continuous (non-pulsatile flow). We did not model continuous flow as the electrical analogy model has not been verified under direct current (DC or continuous flow) conditions.

If an LVAD functions in a pulsatile manner, but independently of the heart, it can be described as functioning in a pseudoasynchronous or isochronous mode. Our analysis predicts that this is potentially highly detrimental to pulmonary flow and pulmonary pressure. This finding explains and confirms previous clinical findings [7], and we would strongly suggest against this mode of operation.

Our model assumes normal valvular function and the absence of cardiac arrhythmias. Atrial fibrillation is quite common clinically and, depending on the mode of LVAD operation, could be quite detrimental, as this situation is analogous to the asynchronous mode of operation. We hypothesize, but we offer no direct evidence, that rate control and pacing a failing heart to create a regular rhythm and operating an LVAD in the counter pulsation mode may offer the best hemodynamic solution.

As the LV ejection fraction reduces to zero, the haemodynamics of cardiac function and the absence of atrial arrhythmias. Atrial fibrillation is quite common clinically and, depending on the mode of LVAD operation, could be quite detrimental, as this situation is analogous to the asynchronous mode of operation. We hypothesize, but we offer no direct evidence, that rate control and pacing a failing heart to create a regular rhythm and operating an LVAD in the counter pulsation mode may offer the best hemodynamic solution.

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The use of an electrical analogy to analyze cardiovascular haemodynamics is well described [15–17] and complements computational fluid dynamics analysis with regard to cardiovascular pressures and flows [18, 19]. Randomized trials are logistically difficult, time consuming and would have to be large to avoid being underpowered due to biological variation, unlike electrical analogies.

LIMITATION

No model can accurately reflect complex biological systems, and our data should be interpreted as such. A strength and a potential weakness of using an electrical analogy is the fact that the effect of biological variation is essentially removed. Simulation assumed no valvular heart disease or intra cardiac shunt such as a patent foramen ovale. Dynamic regulation and interaction between the heart/lung block and the peripheral circulation was not modelled for. At present, the counter pulsation mode of LVAD operation is not routinely available, although working models have been previously described [8].

The model assumed normal right ventricular function, i.e. pure left ventricular dysfunction. This is clinically an unusual situation; however in the clinical setting, any cause of a raised pulmonary artery pressure will be detrimental in the setting of reduced right ventricular function.

LVADs are frequently operational in patients with sepsis and vasodilatation. The electrical analogy model we utilized has not been validated in this scenario and its use may lead to errors.

CONCLUSION

If an LVAD is to be operated in a pulsatile mode, the counter pulsation mode reduces pulmonary artery and left atrial pressure and increases pulmonary blood flow and thus cardiac output. This is in
addition to the reduced right ventricular energetic requirement, a finding previously described. Clinical validation of our findings is necessary.

SUPPLEMENTARY MATERIAL

Supplementary material is available at ICVTS online.

Conflict of interest: none declared.

REFERENCES