Journal of Bioengineering & Biomedical Science
ISSN: 2155-9538
Pirbodaghi, J Bioeng Biomed Sci 2016, S3
DOI: 10.4172/2155-9538.S3-005
Short Communication
Open Access

The Impact of Cannulas on the Heart-Blood Pump Interaction

Tohid Pirbodaghi*

Mechanical Engineering Department, Massachusetts Institute of Technology, 70 Massachusetts Avenue, Cambridge, MA, USA

Abstract

Rotary Blood Pumps (RBPs) as ventricular assist devices (VADs) are connected to the heart by inflow and outflow cannulas; the cannulation is typically performed through the apex of the left ventricle (inflow) and the ascending aorta (outflow). In this study, we investigate the impact of cannulas on heart-pump interaction in vivo. RBPs are characterized by their pressure head and flow rate curves, which give information about what pressures and flow rates the pump can generate at a certain speed. To study how the cannulas (30 ± 5 cm) affect the pump performance, we implanted the CentriMag™ RBP in three sheep via left thoracotomy and cannulated from ventricular apex to descending aorta. Pressure head and flow rate relationship of the pump with and without cannulas at different continuous and pulsatile pump speeds were recorded and analyzed. The results demonstrate high impact of cannulas on the pressure head losses of the pump. For example, at 4 kRPM, while the average pump pressure head is 295 mmHg excluding the cannulas, it becomes 31 mmHg including the cannulas. In general, the higher pump speed, the more pressure loss inside cannulas.

Keywords: Blood pumps; Cannula; *In vivo* study

Introduction

Ventricular assist devices (VADs), which nowadays are mainly based on rotary blood pumps (RBPs), help to improve the blood circulation in patients with weakened ventricle [1-5]. They typically draw the blood from the left ventricular apex and pump it into the circulation through the inflow and outflow cannulas, respectively. While passing through the cannulas, the blood flow dissipates a remarkable portion of its energy received from the pump due to frictional and inertial losses. The frictional losses depend on the material, length, and diameter of the cannulas as well as the blood viscosity; the inertial losses are related to blood mass owing to pulsatility.

RBPs are typically characterized by their pressure head and flow rate curves or so-called the pump function graphs, which give information about what pressures and flow rates the pump can generate. Pump pressure head is usually defined as the difference in pressure between the inlet and outlet of the pump without the connecting cannulas. The cannulas are the primary interface between the device and the patient. In this study, we investigate the impact of cannulas on the pump pressure head. The main objective is to show how the cannulas affect the pump performance. We implanted the CentriMag™ RBP in three sheep via left thoracotomy and cannulated from ventricular apex to descending aorta. We examined pressure head and flow rate relationship of the pump including and excluding the cannulas at different continuous and pulsatile pump speeds.

Materials and Methods

The CentriMag™ RBP was implanted into three healthy female sheep (56-68 kg) using the inflow and outflow cannulas shown in Figure 1.

To modulate the pump speed, a sine waveform with 2000 RPM mean and 1000 RPM amplitude was applied as the pump speed pattern was synchronized with ECG of the native heart. For the sine waveform, the phase shift was varied from 0 to 360 degree with 10 percent increments. A detail description of the pump control program, instrumentation and data acquisition can be found in our previous publications [6,7].

Results and Discussion

Figure 2 shows the pressures measured at the pump inlet, pump outlet, and cannulas tips placed in the left ventricle and aorta while the pump was running at 2 kRPM continuous speed. The pump pressure head without cannulas is the difference between its outlet ant inlet pressures and the head with cannulas is the difference between the pressures at the tips of outflow and inflow cannulas.

Figure 3 shows the average pump pressure head and flow rate relationships including and excluding cannulas effect at different constant speeds over 25 heart cycles for sheep 1 as an example. Excluding cannulas, the results show that the pressure head is directly proportional to the square of the pump speed; for example, at 2 kRPM,

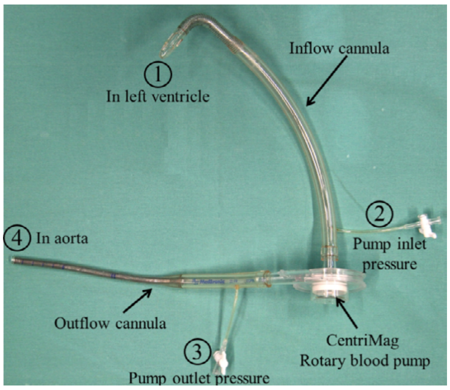

Figure 1: The inflow cannula, a modified 32 Fr angled venous cannula, and the outlet cannula, a 22 Fr arterial cannula, connected to the CentriMag rotary blood pump.

***Corresponding author:** Tohid Pirbodaghi, Massachusetts Institute of Technology, 70 Massachusetts Avenue, Cambridge, MA, USA, Tel: +1 781 810 6643; Fax: +1 781 810 6643; E-mail: pirbodaghi@gmail.com

Received February 19, 2016; **Accepted** March 03, 2016; **Published** March 16, 2016

Citation: Pirbodaghi T (2016) The Impact of Cannulas on the Heart-Blood Pump Interaction. J Bioeng Biomed Sci S3: 005. doi:10.4172/2155-9538.S3-005

the average pressure head is 72 mmHg, while it reaches 295 mmHg at 4 kRPM. Including the cannulas effect, this relationship is not valid anymore. For the pump used in our study, there is no valve in its inlet and outlet resulting in negative flow, backflow, during diastole at 1 kRPM speed. This is caused by the high pressure difference between aorta and LV during diastole and clearly requires a higher speed to be overcome. Backflow through the pump, which increases load on the heart, is potentially dangerous for a weakened heart and must be avoided. Including the effect of cannulas, the mean pressure head increases from 12.4 mmHg at 1000 RPM to 32.7 at 4000 RPM. The average head increases from 16.5 mmHg at 1000 to 295.8 at 4000 RPM excluding the cannulas effect. Moreover, excluding the cannulas, the loops are flatter, thus, there is a smaller span in the pump pressure head.

The average pump pressure head at different constant speeds is listed in Table 1 for all the animals. The higher the pump speed, the greater the impact of cannulas on the pump pressure head and the more energy loss inside the cannulas.

Figure 4 displays the effect of different phase shifts of the pump speed on its pressure head and flow rate relationships with and without cannulas over 25 heart cycles for sheep 1 as an example. The pump was running with a sine waveform with 2 kRPM mean and 1 kRPM amplitude. Excluding the cannulas, the head is always positive with an average of 77.4 ± 7.1 mmHg for all the phase shifts. Including the cannulas, it becomes negative almost during half of a heart cycle due to the energy losses inside the cannulas and its average value decreases to 27.8 ± 4.7 mmHg. Changes in phase shift also affect the flow rate through the pump. Although the pump speed has the same mean and amplitude for all the phase shifts, some of them including phase shifts 0°, 72°, 108°, and 324° result in negative flow.

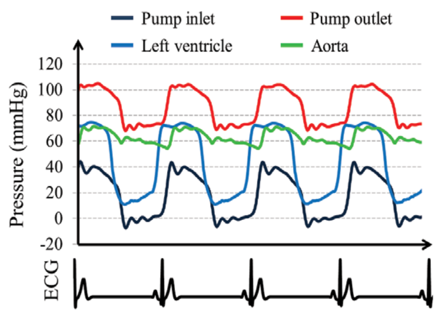

Figure 2: Pressures measured at the pump inlet, pump outlet, and cannulas tips placed in the left ventricle and aorta while the pump was running at 2 kRPM continuous speed.

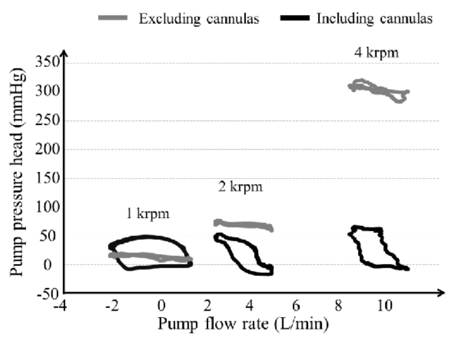

Figure 3: Average pump pressure head and flow rate relationships with and without cannulas at different constant speeds over 25 heart cycles.

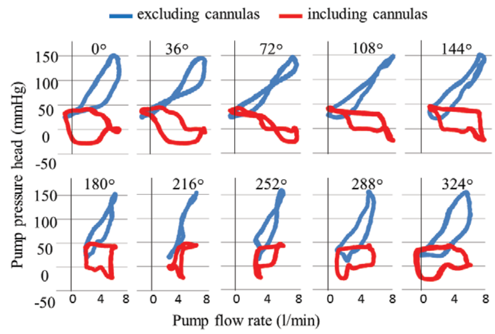

Figure 4: Effect of different phase shifts of the pump speed on its pressure head and flow rate relationships with and without cannulas over 25 heart cycles.

Pump speed	Sheep#1		Sheep#2		Sheep#3	
	including cannulas	excluding cannulas	including cannulas	excluding cannulas	including cannulas	excluding cannulas
1000	7.4	16.5	5.5	13.4	12.0	17.3
2000	18.7	68.9	23.7	65.8	15.3	68.2
3000	29.2	161.6	34.8	161.9	27.3	162.0
4000	32.7	304.1	38.9	324.7	30.5	309.0
5000	19.6	462.1	22.7	472.5	24.3	451.8

Table 1: The average pump pressure head including and excluding the cannulas at different constant speeds.

The results were only presented with specific inflow and outflow cannulas (plastic material and fixed length) in three sheep. Regardless of this limitation, this study highlights the importance of the cannulas in heart-assist device interaction and demonstrates that their role must be carefully considered in defining an effective operating range for the pumps. RBPs are typically designed to produce approximately 100 mmHg pressure head at blood flow between 4 and 5 l/min. However, this working point is affected by the inlet and outlet cannulas. Depending on the cannulas properties such as material, diameter and length, there is a remarkable drop in the pressure head that the pump can deliver for the patient. As a result, it is recommended that the operating range for the pumps should be designed with considering the fact that what kind of cannulas will be used to connect the pump to the heart and aorta.

The cannulas are different in material, surface modifications, lengths, and dimensions and may vary for different pumps, institutions, and applications. For example, HeartMate II and HVAD have inflow cannulas made of titanium or HeartMate XVE and Novacor have outflow cannulas made of porous Dacron. Due to the complexity of cannulas, their tip geometries and placement, a separate study should be performed to analyze the impact of the cannula lengths, shapes, material, and diameters to minimize the energy loss.

It also worth mentioning that for mathematical modeling of cannulas, a combination of an inductor and a resistor is typically used for each cannula, which relates the pressure loss inside the cannula to the flow rate and its time derivative as follows

$$\Delta P = L \times dQ / dt + R \times Q \quad (1)$$

ΔP is the pressure drop and Q is the blood flow rate through the cannula. L and R are inertance and resistance, respectively. For simplified models, values of these components are calculated from the cannula dimensions and blood properties.

$$L = \rho l / \pi r^2 \quad (2)$$

$$R = 8\mu L / \pi r^4 \quad (3)$$

Where l is the length of cannula and *r* is its radius. ρ and μ are blood density and viscosity, respectively.

Conclusion

The impact of cannulas on the heart and assist device interaction was demonstrated by pressure head-flow rate hysteresis loops in vivo. The results indicate the essential role of cannulas in the pump pressure head drop and emphasize their great impact on heart-assist device interaction.

Acknowledgment

The author thanks Levitronix for supplying the pump. The author thank the staff of the Experimental Surgery Institute of the University of Bern.

Conflict of interests

The author reports no conflict of interest. All institutional and national guidelines for the care and use of laboratory animals were followed and approved by the appropriate institutional committees.

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This article was originally published in a special issue, **Design of Biosensors** handled by Editor. Dr. Eduardo De Faria Franca, Federal University of Uberlandia