# Analysis of blood flow in extracorporeal membrane oxygenation circuit

*Erdenejargal ERDENEOCHIR*[1], *Svitlana STRUNINA*[1]

[1] Faculty of Biomedical Engineering, Czech Technical University, Nám. Sítná 3105, 272 01 Kladno, Czech Republic

erdenerd@fbmi.cvut.cz, svitlana.strunina@fbmi.cvut.cz

**Abstract.**

*Extracorporeal membrane oxygenation (ECMO) is the mini invasive circulatory support system. The ECMO circuit consists of an inflow cannula, a blood pump, an oxygenator, an outflow cannula and the pipes.*

*ECMO cannulas provide interface between patient and ECMO system. The Pressure drop vs. flow chart is commonly used to determine the appropriate cannula sizes according to required extracorporeal blood flow.*

*Pressure drop vs. flow charts of the cannulas from the manufacturers are based on evaluations using water as the testing solution.*

*In this study, computational method to indicate the appropriate cannula sizes with blood parameters was used. The cannula sizes for adult patients were investigated.*

*The simulation model indicated that the appropriate sizes for inflow cannulas are 21 Fr when required extracorporeal blood flow is less than 4,5 L/min, 23 Fr less than 6 L/min, 25 Fr less than 7 L/min, 29 Fr and 27 Fr less than 8 L/min.*

*The appropriate sizes for outflow cannulas are 15 Fr when required extracorporeal blood flow is less than 2 L/min, 17 Fr less than 3 L/min, 19 Fr less than 3,6 L/min, 21 Fr less than 4,8 L/min, and 23 Fr less than 5 L/min.*

## Keywords

ECMO, pressure drop, inflow cannula, outflow cannula, blood flow.

## 1. Introduction

Extracorporeal membrane oxygenation (ECMO) represents the minimally invasive circulatory support systen to support or replace failing heart and/or lung function [1]. Extracorporeal membrane oxygenation allow recovery of the function of the lung and the heart, as bridge to transplantation or bridge to decision. The ECMO circuit consists of an inflow cannule, an extracorporeal blood pump, an oxygenator, an outflow cannula and connecting pipes. The principle of the ECMO is deoxygenated venous blood that is drawn from the right atrium, via the inflow cannula, and is pumped by a continuous flow axial or centrifugal pump to the oxygenator where blood gases are exchanged. The oxygenated blood is then returned to the circulatory system via an outflow cannula. Based on the cannula's size, the extracorporeal blood flow in ECMO may reach up to 7 L/min and, could therefore, partially support or even fully substitute for the cardiac pump and pulmonary gas exchange. Placement of ECMO does not necessarily require fluoroscopic guidance and, in emergent situations, can be performed quickly at the patient bedside or in the field [2]. ECMO cannulas provide interface between the patient circulatory system and ECMO circuit.

There are a lot of opinions to recommend cannula size. Nevertheless, because many different cannulas exist, studying the Pressure drop vs. flow chart of each are commonly used to determine appropriate size [3].

Selection of inappropriate cannula size may result in turbulence [4] which destroy red blood cells, can be the cause of microbubbles, induce bubble emboli, bleeding complications and the risk of vascular damage and ischemia [1].

The computational method was used to simulate the cannula pressure drop in the extracorporeal membrane oxygenation system. The pressure drop in various sizes of inflow and outflow cannula for adult patients were investigated. In the model the blood parameters were used.

The main objective of this study is to determine the appropriate inflow and outflow cannula sizes for various extracorporeal blood flow values (EBF) (from 1 L/min to 8 L/min) during the ECMO therapy.

## 2. Materials and methods

The model of cannulas in the ECMO system was modelled in Simulink (see Fig. 1). Simulink is a block diagram environment for modeling and simulation.

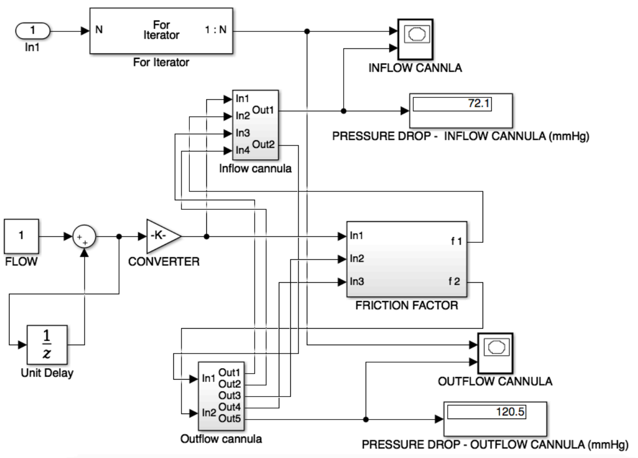


**Fig. 1.** System diagram of the cannula model in the ECMO system.

In this study, the pressure drop in the cannulas was determined by Darcy – Weischbach equation:

$$\Delta p = f \cdot \frac{\rho \cdot L \cdot V^2}{2 \cdot D} \tag{1}$$

where $f$ is Darcy friction factor, $\rho$ is density of the fluid (kg·m$^{-3}$), $D$ is hydraulic diameter of the cannula (m), $V$ is the mean flow velocity (m·s$^{-1}$), and $L$ is cannula length (m).

There are a number of equation to calculate the Darcy friction factor. For this study Blasius correlation was chosen, which is valid for Re < $10^5$

$$f = \frac{0{,}316}{Re^{0{,}25}} \tag{2}$$

where $Re$ is Reynolds number.

Friction factor varies depends on Reynolds number. The Reynolds number is defined as:

$$Re = \frac{r \cdot \rho \cdot v}{\eta} \tag{3}$$

where $\rho$ is density of the fluid (kg·m$^{-3}$), $r$ is radius of the cannula (m), $v$ is velocity of the fluid (m·s$^{-1}$), and $\eta$ is the dynamic viscosity (Pa·s).

The mean flow velocity depends on the volume flow rate value. The flow velocity is directly proportional to the flow and inversily proportional to the sectional area of the cannula.

$$V = \frac{Q}{S} \tag{4}$$

where $Q$ is flow (m$^3$·s$^{-1}$) and $S$ is sectional area of the cannula (m$^2$).

Substitute the equation (4) to the (1) we obtain the equation (5) by calculating the pressure drop in the simulation model

$$\Delta p = f \cdot \frac{\rho \cdot 8 \cdot L \cdot Q^2}{\pi^2 \cdot D^5} \tag{5}$$

where $f$ is Darcy friction factor, $\rho$ is density of the fluid (kg·m$^{-3}$), $D$ is hydraulic diameter of the cannula (m), $L$ is cannula length (m) and $Q$ is flow (m$^3$·s$^{-1}$).

## 2.1 Simulations and Model output

For the simulation purpose the following system parameters were selected: blood dynamic viscosity was 3,6 mPa·s, blood density was 1060 kg·m$^{-3}$ and temperature was 37° C.

The pump volume flow rate was increased from 0 L/min to 8 L/min. The sizes of cannulas were increased from 21 Fr to 29 Fr for inflow cannulas and from 15 Fr to 23 Fr for outflow cannulas for various EBF value. The entire process was repeated for each unique combination of the EBF and cannula sizes.

The output variables consisted of pressure drop value for various sizes of inflow (see Tab. 1) and outflow (see Tab. 2) cannulas. Fig. 2 and Fig. 3 depicts the pressure drop vs. extracorporeal blood flow charts for various sizes of inflow and outflow cannulas. The values are presented in the following units: pressure drop in mmHg and extracorporeal blood flow in L/min.

# 3. Results

The outcomes of simulation have estimated that the appropriate sizes for inflow cannulas are 21 Fr when required extracorporeal blood flow is less than 4,5 L/min, 23 Fr less than 6 L/min, 25 Fr less than 7 L/min, 29 Fr and 27 Fr less than 8 L/min.

The appropriate sizes for outflow cannulas are 15 Fr when required extracorporeal blood flow is less than 2 L/min, 17 Fr less than 3 L/min, 19 Fr less than 3,6 L/min, 21 Fr less than 4,8 L/min, and 23 Fr less than 5 L/min. Fig. 2 and Fig. 3 depicts pressure drop according to the extracorporeal blood flow (EBF) for various cannulas size.

Tab. 1 presents the simulation results of the pressure drop in various inflow cannula size according to various EBF. Tab. 2 presents the simulation results of the pressure drop in various outflow cannula size according to various EBF.

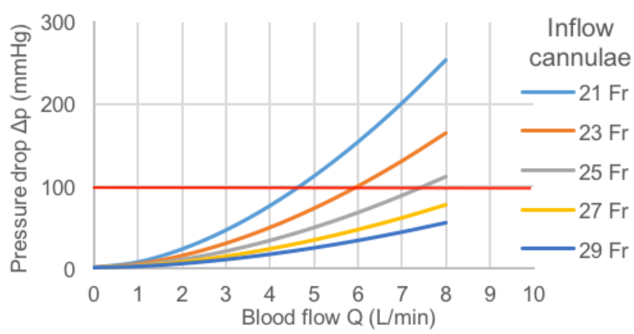

**Fig. 2.** The simulation resalt on created model of the pressure drop according to the EBF for inflow cannulas

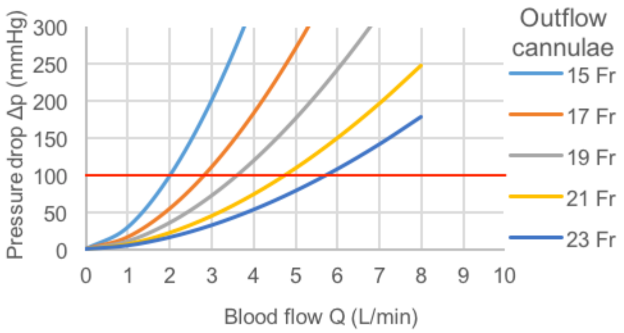


**Fig. 3.** The simulation resalt on created model of the pressure drop according to the EBF for outflow cannulas

| Cannula Diameter (Fr) | Extracorporeal blood flow *Q* (L/min) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | Pressure drop Δ*p* (mmHg) | | | | | | | |
| 15 | 29,20 | 98,23 | 199,70 | 330,40 | 488,30 | 671,80 | 879,80 | 1111,00 |
| 17 | 16,12 | 54,21 | 110,20 | 182,30 | 269,40 | 370,70 | 485,50 | 613,30 |
| 19 | 10,49 | 35,29 | 71,75 | 118,70 | 175,40 | 241,40 | 316,10 | 399,30 |
| 21 | 6,52 | 21,94 | 44,61 | 73,80 | 109,00 | 150,00 | 196,50 | 248,20 |
| 23 | 4,71 | 15,82 | 32,17 | 53,23 | 78,65 | 108,20 | 141,70 | 179,00 |

**Tab. 1.** Pressure drop in inflow cannulas

| Cannula diameter (Fr) | Extracorporeal blood flow *Q* (L/min) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | Pressure drop Δ*p* (mmHg) | | | | | | | |
| 21 | 6,64 | 22,35 | 45,43 | 75,16 | 111,10 | 152,80 | 200,10 | 252,80 |
| 23 | 4,31 | 14,51 | 29,49 | 48,79 | 72,10 | 99,20 | 129,90 | 164,10 |
| 25 | 2,90 | 9,76 | 19,85 | 32,83 | 48,52 | 66,75 | 87,43 | 110,40 |
| 27 | 2,01 | 6,77 | 13,77 | 22,78 | 33,66 | 46,31 | 60,66 | 76,62 |
| 29 | 1,43 | 4,82 | 9,81 | 16,22 | 23,97 | 32,98 | 43,20 | 54,57 |

**Tab. 2.** Pressure drop in outflow cannulas

# 4. Discussion

Nowadays peripheral ECLS cannulas for adults range from 18 to 29 Fr for venous and 13 - 23 Fr for arterial cannulas [5]. In this study the inflow cannulas from 21 Fr to 29 Fr and outflow cannulas 15 Fr to 23 Fr were analyzed.

There are a lot of opinions in relation to cannula size. The size of the cannula is recommended in accordance to the patient anatomic features and the weight or body surface area (BSA)[5]-[7]. In relation to the patient's anthropological parameters - cannula should reach from the peripheral insertion point to a central location. Some data suggest that the cannula size should be determined in relation to the actual size of the vessels [4], [5], [7], [8].

Nevertheless, because many different cannulas exist, studying the flow chart of each are commonly used to determine the appropriate size [3]. The cannula provides a resistance within the ECMO circuit and, therefore, creates a pressure drop (the difference between the pressure entering the cannula and that leaving) across it [9]. The pressure-flow characteristics of cannulas are dependent on their length and internal diameter [10].

Pressure drop vs. flow charts of the inflow and outflow cannulas from the manufacturers are based on evaluations using water as the testing solution [11] at ambient temperature. Patient flow may vary depending on blood viscosity, patient anatomy, and circuit configuration.

With higher pressure across the cannula, there is an increase in jetting at the tip, that can cause intimal damage to the vessel [9]. The high-pressure flow becomes turbulent [4] and damages red blood cells. In addition, it can be the cause of microbubbles [1] and induce bubble emboli.

Thereby, the largest possible cannula can be recommended to be used to maximize blood flow and easily achieve target output. Nonetheless, small cannulas provide support with reduced bleeding complications [37], the risk of vascular damage and ischemia, obstruction of arteries by larger cannula [1].

The size of the cannula is determined in accordance with required EBF, which depend on the patients anatomic features. The pressure drop vs. flow chart are commonly used to determine the appropriate size of cannula for the extracorporeal life support (ECLS) therapy [3].

For constant flow in the ECMO circuit, blood should acquire kinetic energy by the dropping of the total pressure on the other side of the cannula as a result the pressure drop in the cannula occurs. The accepted limit of pressure drop is 100 mmHg. This value should not be exceeded. With higher pressure across the cannula, there is an increase in jetting at the tip that can cause intimal damage to the vessel and hemolysis [5].

The results of this study correspond with data from manufacturers of ECLS cannulas. To verify the results of the simulation the data from Maquet for inflow cannula and from Medtronic for outflow cannula were selected. The results of simulation in this study differed from the manufacturers test results (Maque and Medtronic). The pressure drop vs. flow charts for the arterial and venous cannulas from the manufacturers are based on evaluations using water as the testing solution [6]. In this study human blood parameters were used and was the for cause of the different results.

# 5. Conclusions

An analysis of cannula pressure drop by applying a numerical method is presented in this paper. The simulation case studies were conducted to demonstrate the relationship between cannulas size and pressure drop during various EBF in ECMO system. In this study, the parameters of blood as the testing solution were used. The model used in the present work provides interesting answers to the question of determining the appropriate cannula size for various extracorporeal blood flow values during the ECMO therapy.

# References

[1] Ošťádal Petr and Jan Bělohlávek. ECMO: Extrakorporální membránová oxygenace : Manuál pro použití u dospělých. Praha: Maxdorf 2013.

[2] S. Strunina and P. Ostadal, "Left ventricle unloading during veno-arterial extracorporeal membrane oxygenation," Current Research: Cardiology, vol. 3, pp. 5-8, 2016.

[3] P. G. Menon et al. Aortic outflow cannula tip design and orientation impacts cerebral perfusion during pediatric cardiopulmonary bypass procedures. Ann Biomed Eng 41(12), pp. 2588-2602. 2013. Available: http://link.springer.com/article/10.1007/s10439-013-0857-8. DOI: 10.1007/s10439-013-0857-8.

[4] K. Kohler et al, "ECMO cannula review," Perfusion, vol. 28, pp. 114-124, 2013.

[5] A. Beckmann et al. Position article for the use of extracorporeal life support in adult patients. Eur J Cardiothorac Surg 40(3), pp. 676-680. 2011. . DOI: 10.1016/j.ejcts.2011.05.011.

[6] M. Bonacchi et al, "A novel strategy to improve systemic oxygenation in venovenous extracorporeal membrane oxygenation: The "χ-configuration"," J. Thorac. Cardiovasc. Surg., vol. 142, pp. 1197-1204, 2011.

[7] G. Grasselli et al, "Percutaneous vascular cannulation for extracorporeal life support (ECLS): a modified technique," Int. J. Artif. Organs, vol. 33, pp. 553-557, Aug, 2010.

[8] L. Lequier et al. Extracorporeal membrane oxygenation circuitry. Pediatr Crit Care Med 14(5 0 1), pp. 7. 2013. Available: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3742331/. DOI: 10.1097/PCC.0b013e318292dd10.

[9] B. Lich and D. Brown, The Manual of Clinical Perfusion (Second Edition Update). FortMyers, FL: Perfusion.com, 2004.

[10] D. S. Foley et al, "Percutaneous cannulation for pediatric venovenous extracorporeal life support," J. Pediatr. Surg., vol. 35, pp. 943-947, 2000.

[11] F. Qiu et al, "Hemodynamic evaluation of arterial and venous cannulae performance in a simulated neonatal extracorporeal life support circuit," Perfusion, vol. 26, pp. 276-283, 2011.