DOI: https://doi.org/10.46354/i3m.2019.iwish.001

# CFD ANALYSIS OF PERIPHERAL ECMO CANNULATION

**Fragomeni G.**[(a)]**, Rossi M.**[(b)]

[(a)] Medical and Surgical Sciences Department, “Magna Graecia” University, Catanzaro, Italy
[(b)] Cardiac Surgery Department, Grande Ospedale Metropolitano “Bianchi-Melacrino-Morelli”

[(a)]fragomeni@unicz.it, [(b)]michele.r@libero.it

## ABSTRACT

ECMO (Extra Corporeal Membrane Oxygenation) is a technique supporting vital functions through extracorporeal circulation, by raising blood oxygenation, reducing the blood values of carbon dioxide (CO2), increasing cardiac output and acting on body temperature. In conditions of severe respiratory and/or cardiac insufficiency, it allows to rest heart and lungs while performing their ventilation and pump functions.

The most common sites for establishing peripheral ECMO are femoral artery and vein. The main goal of ECMO cannulation is to provide the least traumatic and most durable and simplified method for delivering the blood to and from the circuit.

There are several ways to connect ECMO to the venous/arterial system. The present study’s aim is to analyse one connection by anastomoses and another one by cannula through a Computational Fluid Dynamics (CFD) model.

Keywords: Femoral cannulation, CFD, ECMO, hemodynamics

## 1. INTRODUCTION

Basically, ECMO is made up of a pump, an oxygenator and a blood heater. The extracorporeal tecnique is performed by the cannulation of central (usually internal or femoral jugular) veins and artery. Thus, it is possible to distinguish between two main types of Ecmo, even if others exist:

- VV-ECMO (veno-venous): it supports lung function by ventilation and oxygenation of the blood. It is usually performed through vascular accesses in the internal jugular vein and femoral vein. Moreover, it can be used in conditions of severe respiratory failure only if cardiac function is preserved, not providing any hemodynamic – if not indirect - support.
- VA-ECMO (veno-arterial): it also supports the heart pump function. Through vascular accesses in the femoral artery and vein, it supports circulation as well, having a direct hemodynamic action, acting on cardiac output and, therefore, on blood pressure directly; it is indicated in the management of severe systemic hypoprofusion pictures and in cardiopulmonary resuscitation.

The most frequent complication of the method is arterial hemorrhage in va-Ecmo, followed by hemolysis and thrombocytopenia depending on pump speed with consequent mechanical damage, thrombotic and thromboembolic problems, sepsis and gas embolism; in va-Ecmo the risk of ischemia of the lower limb is very high, due to the large caliber of the cannula positioned in the femoral artery.

The new investigation techniques and the need to organize and interpret an increasing amount of biological information and data represent a remarkable opportunity for the use of computational and statistical methods and models, in biological and biomedical research and in the understanding of medical problems (diagnostics, epidemiology, clinical medicine…)

Analysis and numerical simulation of mathematical models in the more general context of life sciences is slowly emerging as an additional investigative tool to be used alongside other experimental or theoretical methods. Indeed, there are several studies in the fields of biomechanics, hemodynamics, artificial organs and prosthesis design (Pascoletti 2018, Zanetti 2013, Zanetti 2017, Aldieri 2018, Caruso 2015, Ambrogio 2015, Campobasso 2018).

Even if the survival rate is high, cerebrovascular injury and/or lower limb pathologies may be important complications. In fact, the significant changes in circulation that happen during induction of ECMO (compared with the previous state - patient is hypoxemic for hours) are often responsible for irreversible damage (Papademetriou 2011). Although several studies were carried out to investigate the position of the cannulae (Mazzitelli 2016) or to analize the flow through the cannulae (De Bartolo 2011), there are no studies that analize the differences between the insertion of a cannula and the realization of an anastomosis for the use of ECMO.

A computational approach was employed to carry out the investigation on a 3D patient-specific femoral artery model by means of Computational Fluid Dynamics (CFD) simulations. In our model we compared the blood flow distribution of the interposition graft for VA ECMO simulating a connection by means of cannula and an anastomosys.

## 2. MATERIALS AND METHODS

During VA ECMO assistance, the ECMO system is connected to the patient's vascular system through the femoral artery (Fig.1).

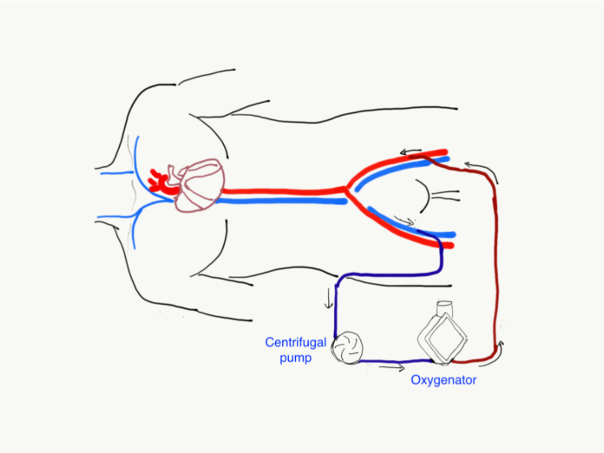
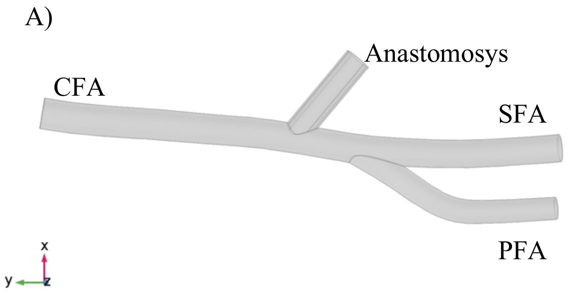


Figure 1: ECMO connection scheme

In the present study finite element models were analyzed to verify haemodynamic behaviour when either a cannula (Case A) or an anastomosis (Case B) is used to connect the femoral artery.

### 2.1. Geometrical Model

The geometrical model was realized by means of commercial CAD Software starting from anatomical data (vessel caliber and lenght) (Czyżewska 2012). The cannula was created using reverse engineering techniques, whereas the arteries were reconstructed starting from DICOM images. The model reproduced Common Femoral Artery (CFA), Superficial Femoral Artery (SFA), and Profound Femoral Artery (PFA) as showed in Figure 1. The diameter of the anastomosis is 8 mm, whereas the cannula has a diameter of 16 Fr and ends with a curved tip. The results may be influenced also by other factors, such as the angle and position of the cannula and anastomosis. In this work the same angle and position values were used for both the cannula and the anastomosis, so as to evaluate only the difference between the two solutions.



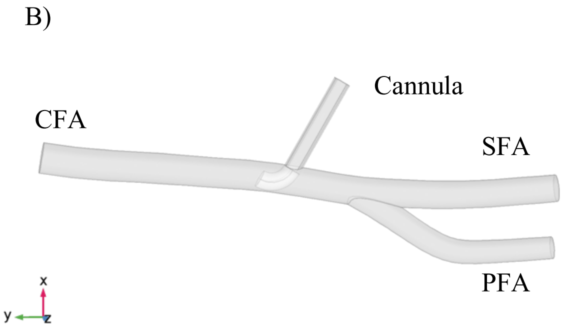


Figure 2: a) Geometrical model for a) anastomosis and b) cannula connection.

### 2.2. Mesh

The domain was discretized with tetrahedral, pyramidal, triangular and prismatic element (table1), with an amount of ~ 2,000,000 elements for each model, as shown in Figure 2. Boundary layer mesh elements have been used along the no-slip boundary.

Table 1: Mesh statistics

| | **Case A** | **Case B** |
|---|---|---|
| Minimum element quality | 0.001823 | 0,001704 |
| Average element quality | 0.5191 | 0.5197 |
| Tetrahedral elements | 284835 | 331160 |
| Pyramid elements | 1454 | 3298 |
| Prism elements | 1433306 | 1660420 |
| Triangular elements | 25456 | 30254 |
| Quadrilateral elements | 732 | 648 |
| Edge elements | 947 | 1201 |
| Vertex elements | 20 | 32 |

The number and distribution of the mesh elements was optimized to give a $10^{-5}$ error under any investigated condition, generally obtained with a number of elements in excess of $2.5 \cdot 10^6$. The mesh was optimized by analyzing the error trend as a function of calculation time.

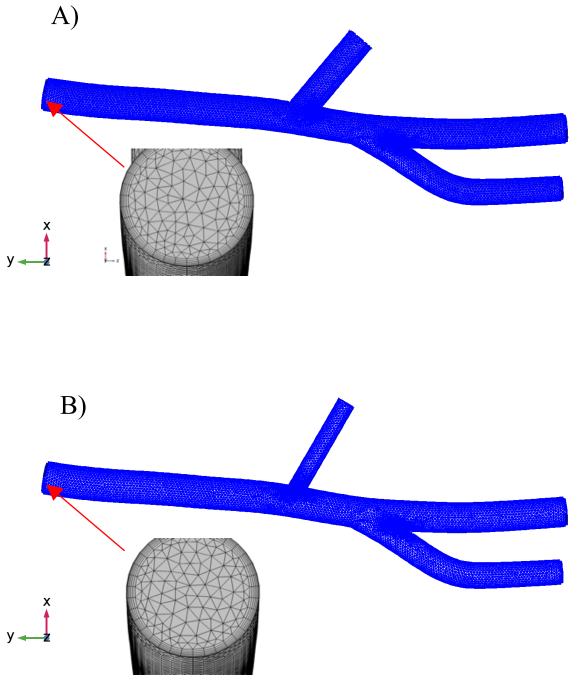


Figure 3: Model mesh for a) Case A and b) Case B

### 2.3. Boundary conditions

As boundary condition, the same mean inlet flow of about 2.5 L/min was applied in the two cases, whereas zero-pressure conditions were set as outlets in all vessels, as in similar comparative studies (Caruso et al. 2017, Karmonik et al. 2012, Lawford 2008).

### 2.4. Simulations details

Numerical computations were performed using the steady three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations and the low-Reynolds k-ω turbulence model. Turbulence effects are modeled using the Wilcox revised two-equation *k*-ω model with realizability constraints (Wilcox 2002). That model solves for the turbulent kinetic energy, k, and ω is the dissipation per unit turbulent kinetic energy:

$$\rho\frac{\partial k}{\partial t}+\rho\mathbf{u}\cdot\nabla k=P_k-\rho\beta_0^{*}k\omega+\nabla.\left(\left(\mu+\sigma_k^{*}\mu_{\mathrm{T}}\right)\nabla k\right),$$

$$\rho\frac{\partial\omega}{\partial t}+\rho\mathbf{u}\cdot\nabla\omega=\alpha\frac{\omega}{k}P_k-\beta_0\rho\omega^2+\nabla.\left(\left(\mu+\sigma_\omega\mu_{\mathrm{T}}\right)\nabla\omega\right).$$

where u is the velocity field, p the pressure, k Turbulent kinetic energy and ω is the specific dissipation rate. α, $\sigma_\omega$, $\sigma_\kappa^*$, $\beta_0$, $\beta_0^*$ are the auxiliary parameters for Wilkox revised k-w. The turbulent viscosity is defined as:

$$\mu_{\mathrm{T}}=\rho\frac{k}{\omega}$$

Blood can be approximated with a Newtonian and incompressible fluid (Caruso 2017, Condemi 2016, Gaudio 2017).

COMSOL 5.4 (COMSOL Inc, Stockholm, Sweden), a commercial software package based on finite elements method, was used to carry out the computational studies, for the postprocess and to visualize the results.

Because simulations were performed on a Workstation equipped with a 64 GB RAM and two Intel Xeon E5-2630 v3 2.40 GHz processors, the computational time for each CFD analysis was approximately 3 hours.

## 3. RESULTS

Streamlines of the flow distribution with velocity magnitude on the CFA, SFA and PFA are illustrated in Figures 4 and 5.

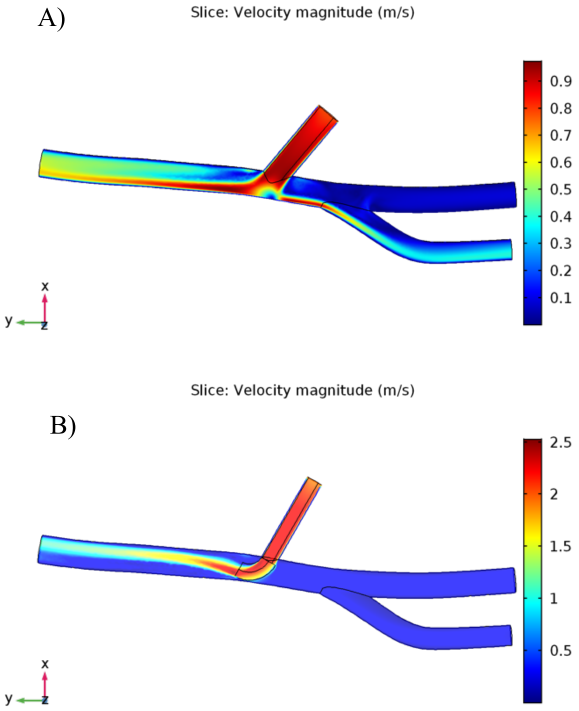


Figure 4: Velocity Magnitude a) Case A b) Case B.

Both in Case A and in Case B, blood flow from the ECMO system is mainly oriented towards the upper part of the body, even if in Case B a small direct flow towards the lower limbs, and particularly in the Profound Femoral Artery, can be noticed.

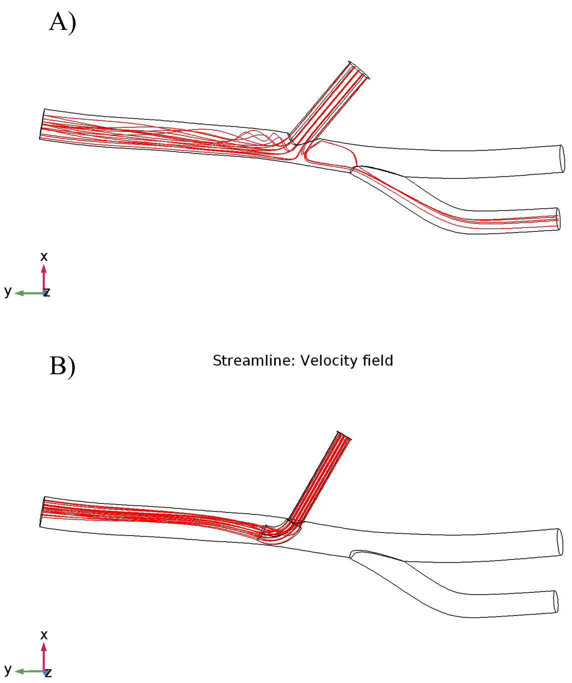


Figure 5: Streamlines a) Case A b) Case B.

Table 2 shows the percentage distribution of the flows in the arteries considered in the model. Also this table highlights quantitatively how the flow from the pump is mainly directed towards the upper part of the body.

Table 2: Comparison between Case A and Case B in terms of flow rates.

| | **Case A** | **Case B** |
|---|---|---|
| Common Femoral Artery | 74,0% | 99,7% |
| Superficial Femoral Artery | 6,0% | 0,2% |
| Profound Femoral Artery | 20.2% | 0,1% |

Moreover, to better understand the influence of ECMO on femoral artery hemodynamics, the wall shear stress (WSS), which is the friction force created by blood motion on vessel walls, was evaluated according to equation reported in Caruso et al. (2015).

The physiological level of WSS is about 1.5-2.0 Pa, (Malek et al. 1999), whereas values less than 0.481 Pa are considered as low and correlated to atherosclerotic place formation (Lee et al. 2008).

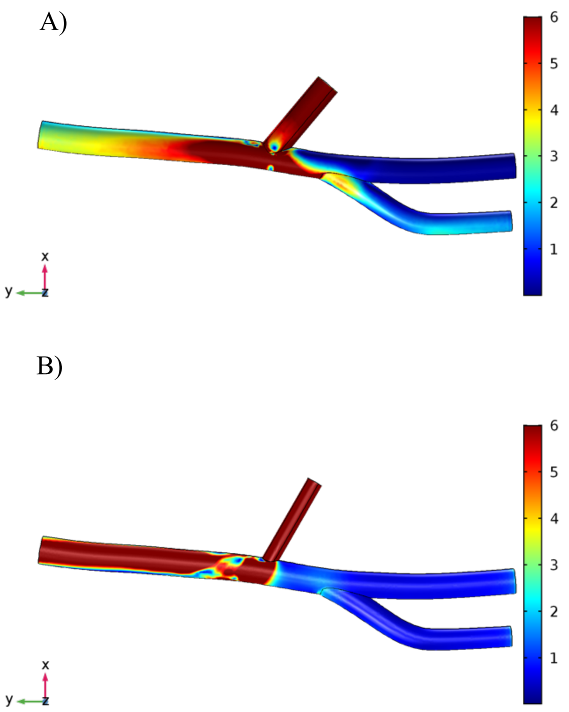


Figure 6: Viscous stress (Pa) a) Case A b) Case B.

## 4. DISCUSSIONS

During peripheral VA ECMO, one of the complications of retrograde flow into femoral artery is lower limb ischemia. The results show that when using anastomoses (Case A) the flow can be distributed both towards the upper part of the body and towards lower limbs (Figures 4a and 5a), whereas when using a cannula the flow is almost completely directed towards the upper part (Figures 4b and 5b).

Particularly, if the connection is made by anastomoses, 74% of the flow from ECMO flows towards the upper part of the body, whereas 26% is directed towards the lower limbs ( 20% through SFA and 6% through PFA). In the case of anastomoses (Case A), it is possible to vary the angle between the duct coming from the pump and the femoral artery so as to vary the flows towards the lower part of the body (in the case in question we considered a 60° angle). When a cannula was used (Case B) for connection to the pump the flow was almost completely oriented towards the upper part of the body (more than 99%), whereas from SFA and from PFA the flow was almost zero. In this configuration, even varying the inclination of the cannula with respect to the axis of the femoral artery, no significant variations of flow rates would be obtained. In fact, most of the flow would be oriented towards the upper part of the body anyway, which might cause some problems both in the lower limbs (hypoperfusion) and in the brain (hyperperfusion).

The femoral artery surface in both Case A and Case B had a similar WSS distribution. In detail, the CFA vessel is subjected to high WSS (>5 Pa), whereas the surfaces around SFA and PFA presented a very low value (≈ 0 Pa).

Starting from these results it can be seen how using an anastomosis it is possible to better modulate the fluid by seeking an optimal distribution of the flow between the upper and lower parts of the body. Furthermore, it is possible to make the correct flow flow exactly in the various districts by creating artificial occlusions to the SFA and PFA (i.e. by means of clamps).

## 5. CONCLUSION

The use of interposition graft allows limb perfusion but with significant blood loss central perfusion. A better central blood flow support can be achieved by varying the anastomosis insertion angle so as to correctly distribute the flow towards the lower limbs in oder to avoid unwanted effects.

From the analyzed results it can also be deducted that if an accidentally erroneous tilt angle of anastomosis is used cerebral blood flow or lower limb perfusion will decrease, thus creating potential problems for the patient. Therefore, since many patients suffer from impaired autoregulation, this study can support diagnostic tools (Lu 2014, Caruso 2015), helping to optimize support conditions based on patient-specific assessment and thereby improving the patient's outcome. Future developments might also include analyzing the influence of cannula and anastomosis positions and the validation of the model with clinical data.

## REFERENCES

Ambrogio, G., Conte, R., De Napoli, L., Fragomeni, G., Gagliardi, F. Forming approaches comparison for high customised skull manufacturing (2015) Key Engineering Materials, 651-653, pp. 925-931

Aldieri A., Terzini M., Osella G., Priola A.M, Angeli A., Veltri A., Audenino A., Bignardi C. "Osteoporotic hip fracture prediction: is T-score based criterion enough? A Hip Structural Analysis based model", Journal of Biomechanical Engineering 2018 1 Nov, 140(11)

Caruso, M.V., Gramigna, V., Serraino, G.F., Renzulli, A., Fragomeni, G. Influence of aortic outflow cannula orientation on epiaortic flow pattern during pulsed cardiopulmonary bypass (2015) Journal of Medical and Biological Engineering, 35 (4), pp. 455-463

Caruso, M.V., Renzulli, A., Fragomeni, G. Influence of IABP-Induced Abdominal Occlusions on Aortic Hemodynamics: A Patient-Specific Computational Evaluation (2017) ASAIO Journal, 63 (2), pp. 161-167

Campobasso, R., Condemi, F., Viallon, M., Croisille, P., Campisi, S., Avril, S. Evaluation of Peak Wall Stress in an Ascending Thoracic Aortic Aneurysm Using FSI Simulations: Effects of Aortic Stiffness and Peripheral Resistance (2018) Cardiovascular Engineering and Technology, 9 (4), pp. 707-722.

Condemi, F., Wang, D., Fragomeni, G., Yang, F., Zhao, G., Jones, C., Ballard-Croft, C., Zwischenberger, J.B. Percutaneous double lumen cannula for right ventricle assist device system: A computational fluid dynamics study (2016) Biocybernetics and Biomedical Engineering, 36 (3), pp. 482-490

Czyżewska, Dorota et al. "Ultrasound assessment of the caliber of the arteries in the lower extremities in healthy persons - the dependency on age, sex and morphological parameters of the subjects." *Journal of ultrasonography* vol. 12,51 (2012): 420-7. doi:10.15557/JoU.2012.0030.

De Bartolo, C., Nigro, A., et al. Numerical and experimental flow analysis of the Wang-Zwische double-lumen cannula (2011) ASAIO Journal, 57 (4), pp. 318-327

Gaudio, L.T., De Rosa, S., Indolfi, C., Caruso, M.V., Fragomeni, G. Hemodynamically Non-Significant coronary artery Stenosis: A predictive model (2017) 6th International Workshop on Innovative Simulation for Health Care, IWISH 2017, Held at the International Multidisciplinary Modeling and Simulation Multiconference, I3M 2017, pp. 26-30

Karmonik C., Partovi S., Loebe M., Schmack B., Ghodsizad A., Robbin M.R., ... Lumsden A.B., 2012. Influence of LVAD cannula outflow tract location on hemodynamics in the ascending aorta: a patient-specific computational fluid dynamics approach. ASAIO Journal, 58(6), 562-567.

Lawford P.V., Ventikos Y., Khir A.W., Atherton M., Evans D., Hose, D.R., ... Hollis A.P., 2008. Modelling the interaction of haemodynamics and the artery wall: current status and future prospects. Biomedicine & Pharmacotherapy, 62(8), 530-535.

Lu, Y. H., Chen, C. Y., Menon, P. G., Liu, K. T., & Lin, H. H. (2014). Hemodynamic effects of endoleak formation in abdomi- nal aortic aneurysm patients with Stent-Graft implants. Journal of Medical and Biological Engineering, 34(6), 554–558.

Lee S.W., Antiga L., Spence J.D., Steinman D.A., 2008. Geometry of the carotid bifurcation predicts its exposure to disturbed flow. Stroke, 39(8), 2341-2347.

Malek A.M., Alper S.L., Izumo S., 1999. Hemodynamic shear stress and its role in atherosclerosis. Jama, 282(21), 2035-2042.

Mazzitelli, R., Boyle, F., Murphy, E., et al.Numerical prediction of the effect of aortic Left Ventricular Assist Device outflow-graft anastomosis location (2016) Biocybernetics and Biomedical Engineering, 36 (2), pp. 327-343

Papademetriou M. D. 2011. Multichannel Near Infrared Spectroscopy to monitor cerebral oxygenation in infants and children supported in extracorporeal membrane oxygenation (ECMO). Thesis (Ph.D). University College London.

Pascoletti, G., Cianetti, F., Putame, G., Terzini, M., Zanetti, E.M. Numerical simulation of an intramedullary Elastic Nail: Expansion phase and load-bearing behavior (2018) Frontiers in Bioengineering and Biotechnology, 6, art. no. 174

Zanetti, E.M., Bignardi, C. Mock-up in hip arthroplasty pre-operative planning (2013) Acta of Bioengineering and Biomechanics, 15 (3), pp. 123-128

Zanetti, E.M., Terzini, M., Mossa, L., Bignardi, C., Costa, P., Audenino, A.L., Vezzoni, A. A structural numerical model for the optimization of double pelvic osteotomy in the early treatment of canine hip dysplasia (2017) Veterinary and Comparative Orthopaedics and Traumatology, 30 (4), pp. 256-264

Wilcox D., Turbulence Modeling for CFD, 3rd ed. 2002: DCW Industries.

.

## AUTHORS' BIOGRAPHY

**Gionata Fragomeni**

He graduated in Engineering at the University of Calabria in 1997 and got a PhD in Bioengineering at the University of Bologna in 2003.
He was a temporary professor in Cardiovascular Mechanics and Mechanics for Biomedical Applications at Calabria University and Magna Graecia University. He is an Assistant Professor at the Faculty of Medicine at Magna Graecia University of Catanzaro.
Prof. Gionata Fragomeni was the coordinator of two national research projects financed by the Italian Ministry of Research, and has authored over 100 publications on journals and international conference proceedings. His research interests include Bio-Fluid Dynamics, Computer Modeling and Cardiovascular Mechanics.

**Michele Rossi**

He graduated in Medicine and Surgery at the University of Naples "Federico II" in 1999 and got a PhD in Bioengineering at the University of Catanzaro "Magna Graecia" in 2016.
He was trained in cardiac surgery both in Italy at "Federico II" University of Naples and in the United Kingdom where he spent about seven years as a fellow in the following centers: Queen Elizabeth Hospital in Birmingham; Royal Sussex County Hospital in Brighton and the John Radcliffe Hospital in Oxford. He joined the retrieval team for heart and lung transplantation and, since the beginning of his abroad fellowship, he has been involved in assisted mechanical circulation. In 2011 he returned back to Italy to work as cardiac surgeon, first at University Magna Graecia of Catanzaro and then, from 2016 at the new born Heart Center in Reggio Calabria, as senior staff surgeon.
Dr. Rossi is an active member of EACTS (European Association of Cardio-thoracic Surgeons) since 2009. He has authored over 100 publications on journals and international conference proceedings. His research interests include Bio-Fluid Dynamics, Computer Modeling and Cardiovascular Mechanics.