IJAO
ISSN 0391-3988

Int J Artif Organs 2017; 40(10): 558-562
10.5301/ijao.5000618

ORIGINAL RESEARCH ARTICLE

Particle image velocimetry tests on pediatric 45-cc and 30-cc ventricle assist devices: effects of heart rate on VAD operation

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ABSTRACT

Background: This study investigated flow analysis inside pediatric ventricle assist devices (VADs) designed and manufactured at the Foundation for Cardiac Surgery Development (FRK), Zabrze, Poland. The main goal of the experiment was to define the minimal heart rate admissible in clinical practice.

Methods: The flow was directed by mechanical, single-disc valves developed at the Lodz University of Technology, Institute of Turbomachinery in Lodz, Poland. VAD operation conditions under different heart rates were analyzed. Measurements were performed on Religa PED pediatric VADs (45 cm^3 and 30 cm^3) with a particle image velocimetry (PIV) system.

Results: Due to the PIV method used, the measurements were made without interference of the measuring system onto the flow structure in the investigated channel, as the measurement procedure is noninvasive. During the investigations conducted in different measurement planes, the majority of the flow volume in the chamber was observable.

Conclusions: The measurements at different heart rates demonstrated a significant influence of this parameter on the flow nature in the heart ventricle. Additionally, it was found that the heart rate affected the operation of heart valves in the VAD.

Keywords: Heart rate, Pediatric ventricle assist device, Particle image velocimetry, PIV, VAD

Introduction

Heart diseases are reported to be one of the most common causes of death. According to the American Heart Association Statistics Committee and the Stroke Statistics Subcommittee, 2,804 heart transplants were performed in the US in 2015, with 4,011 people on a waiting list in 2015 (1, 2). In the group of people who received a transplant, only 10% of children under the age of 10 years. Due to an insufficient number of donors, investigations on pediatric ventricle assist devices (VADs) have been conducted for many years in various centers. The success of long-term support with implantable VADs in adults and children has led to their increasing use not only as a bridge to transplantation in patients but also as a bridge to recovery (3). All support structures of pediatric VADs require a series of tests before their application in clinics. In the case of the VAD, an influence of its structure on the pumped blood is a particularly important criterion for verifying the suitability of the design. Activation and blood cell hemolysis are 2 phenomena that designers are trying to restrict. These two mechanisms occur due to contact of blood with the implanted prosthesis, but their occurrence is highly affected by the flow structure within the VAD. The blood cell activation may result in blood coagulation on the walls of the VAD, but also cause blood clots which can block the flow in arteries. Hemolysis reduces the number of properly formed red blood cells, which decreases the effectiveness of a gas exchange in cells (4-9).

VAD operational conditions under different heart rates (HR) were analyzed. The flow in blood chambers of pediatric 45-cc and 30-cc VADs, which were designed at the Z. Religa Foundation for Cardiac Surgery Development (FRK), Zabrze, Poland, and equipped with disc valves developed in cooperation with the Institute of Turbomachinery, Lodz University of Technology (10-12) was investigated experimentally. The Religa Heart PED ventricle assist device is a pneumatic pump and it consists of 2 chambers separated by an impermeable membrane. The VAD with a single inlet nozzle is supplied with

Accepted: June 9, 2017
Published online: July 8, 2017

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air. The air overpressure and underpressure forces the membrane separating air from blood to move, enforcing simultaneously the blood flow in the blood chamber of the ventricle. The air overpressure forces the blood flow from the blood chamber, whereas the underpressure makes the blood flow into the chamber. The flow direction is controlled by 1-way disc valves. Due to the structure of the ventricle, it is possible to attain a pulsating flow, very close to the human physiological one. The shapes of the Polish VADs Religa PED45 and Religa PED30 are new, original designs. Visually they are similar to other chambers, but the difference lies in the details. The blood chamber and artificial heart valves were developed on the basis of numerical studies and they were tested experimentally. A novelty in this paper lies in the detection and quantification of areas of stagnation by means of particle image velocimetry (PIV) measurements.

Methods

Two pulsating pediatric ventricle assist devices, the Religa Heart PED 45 and the PED 30, were subject to investigation. The numbers 45 and 30 denote the blood discharge volume expressed in cm^3. The PED 30 VAD is designed for children from 4 to 9 years old, whereas the PED 45 VAD can be used in 8 to 12 year-old children. The VADs are made of transparent polyurethane. This transparency is indispensable during tests employing a PIV system. The PED 30 VAD has a 16 mm Moll valve assembled in the inlet channel and an 18 mm Moll valve in the outlet channel. The PED 45 VAD has an 18 mm Moll valve in the inlet channel, and a 20 mm Moll valve in the outlet channel (3, 13-16). The structure inside the blood chambers was measured with the PIV 2-dimensional method, in subsequent planes 2 mm distant from each another. The measurements were conducted in the planes parallel to the inlet and outlet channel axes. In the present study, the flow at the distance of measurement planes from the reference plane determined as tangent to the upper air chamberequal to 23, 25 and 26 mm, respectively (Fig. 1A), for the PED 30 valve is described. The distances of measurement planes from the reference one for the PED 45 valve are equal to 15, 17 and 19 mm, correspondingly (Fig. 1B).

The measurements on the test stand (Fig. 2) were conducted with a LaVision FlowMaster system. This system evaluates 3-dimensional velocity vector fields from scattered light patterns of particles or droplets seeded into the flow (liquid or gas). LaVision FlowMaster camera systems can record 2 successive images within a min. time <100 nanoseconds for ultrafast cross-correlations and speeds up to Mach 4. The main data of the system are as follows: the frequency of laser pulse generation up to 10 kHz; the pulse frequency up to 2 × 200 mJ; the frequency of camera transfer up to 3 kHz (17). A 40% aqueous glycerine solution having density and viscosity close to blood was used as the flow medium. The wave length is equal to 532 nm. An initial interrogation region size was 32 × 32 pixels, with a final size of 16 × 16 pixels and a 50% overlap region. As seeding particles, hollow glass spheres with a diameter between 3 and 10 µm and a density between 1.05 to 1.15 g/cm^3 were used. Table I shows the measurement parameters applied during the tests. The VAD operation was controlled with a POLPDU 402 controller supplied by FRK, which is used in clinical practice and dedicated to FRK pneumatic chambers. From the numerical calculations, it is known that the best angular position is equal to 30° for the inlet valve and 150° for the outlet valve (18).

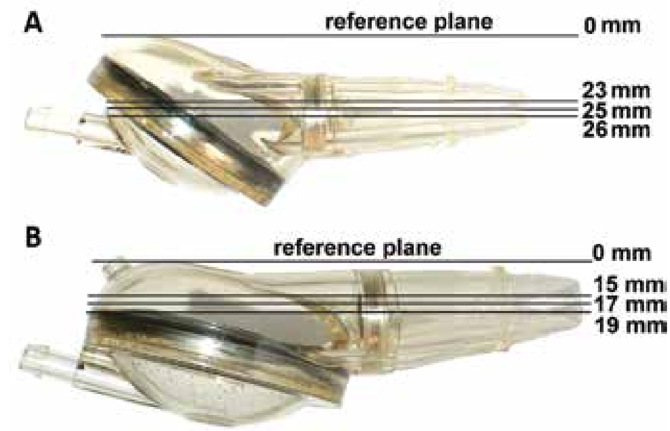

Fig. 1 - Measurement planes: (**A**) PED 30, (**B**) PED 45.

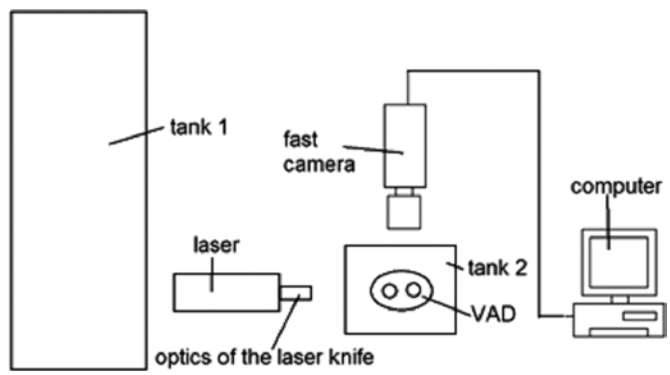

Fig. 2 - Scheme of the test stand.

TABLE I - Measurement parameters

Flow medium	40% aqueous glycerine solution
Flow medium temperature	37°C
Flow medium density	1.06 g/cm^3
Heart rate	30, 40, 50, 60, 70, 80 beats per minute
Systole to diastole percentage	40%, 45%, 50%
Camera frequency	800 Hz
Time between pulse A and pulse B of the laser	400 µs
Pressure in the controller	150/-20 Pa

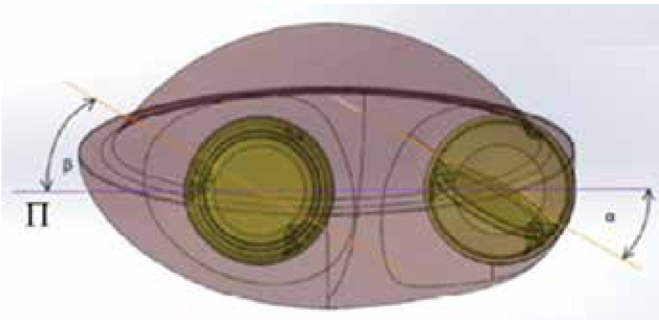

Fig. 3 - Definition of the angular position of valves (18).

The angular position of the valve is defined by the angle between the plane passing through the axis of rotation of the disc in the plane perpendicular to the valve ring and the plane π (Fig. 3). The angle α denotes a position of the inlet valve, whereas the angle β refers to a position of the outlet valve (18). The operation of the ventricular assist device can be divided into 2 phases – a filling phase and an ejection phase. The filling phase begins with an upward movement of the membrane to the surface of the pneumatic chamber. The inlet valve is fully open, the outlet valve begins to close. The filling phase ends with the membrane touching the surface of the pneumatic chamber, with the outlet valve closed. When the membrane starts to move downwards in direction of the surface of the blood chamber, the ejection phase begins. Then, the outlet valve starts to open and the inlet valve is closing. In the middle of the ejection phase, the outlet valve is fully open, whereas the inlet valve is closed. At the end of the ejection phase, instead of moving, the membrane deforms elastically.

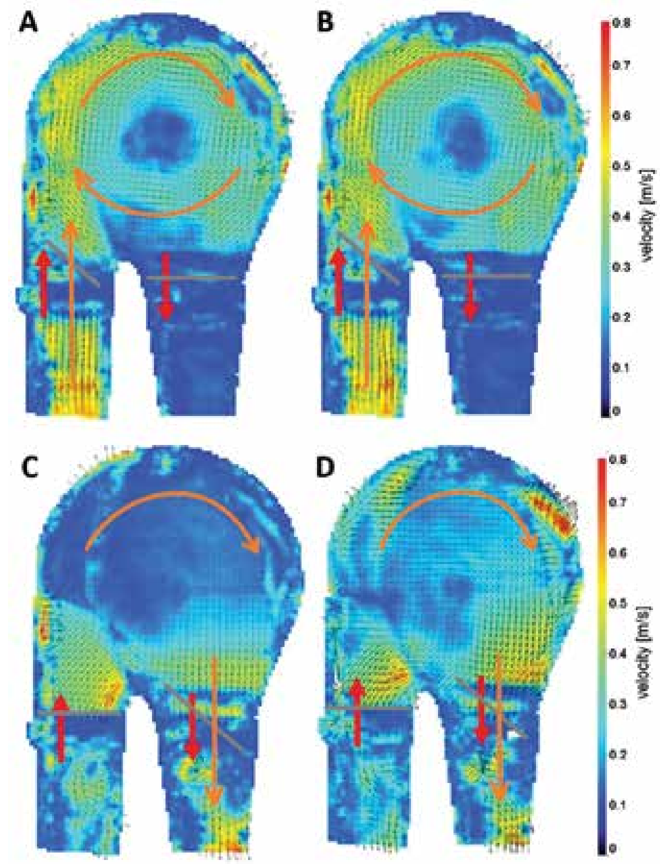

Fig. 4 - PED45, velocity distribution: (**A**) filling phase, HR 40, S/D% 45; (**B**) filling phase, HR 40, S/D% 50; (**C**) ejection phase, HR 30, S/D% 40; (**D**) ejection phase, HR 60, S/D% 40.

Results and discussion

The PIV method, despite its numerous advantages, has also some limitations, typical of optical methods. One of them is a limited possibility to observe regions near the wall with high resolution, mainly due to reflections of the laser light. The second limitation lies in a statistical approach to the data analysis. The method is based on particle tracking, thus one needs a set of successive images to determine velocity vector components. Each measurement result shown in the paper is the average result taken from 100 images. One image is a time interval, which takes 0.00125 seconds. Hence, the results shown in the figures are vector plots determined as dominant over a time interval of 0.125 seconds. Knowing the limitations of the method used, we conclude that the larger the % of stagnation is, the more probable that blood will remain at a certain spot, thus the % of stagnation is a parameter illustrating the potential risk of thrombosis.

A comparison of the results for various heart rates and various systole to diastole percentages (S/D%) reveals significant differences in the flow structure both in the filling and ejection phases of the VAD operation. Figure 4A shows a velocity distribution in the filling phase for 45% and 50% S/D% at a steady value of the heart rate. Gray lines represent the position of the heart valve, whereas orange lines refer to the flow direction of the medium. A velocity distribution on the 25-mm plane for both S/D% under investigation looks similar. The maximal velocity is equal to 0.55 m/s in the ventricle and 0.65 m/s in the inlet channel. A more uniform velocity distribution was attained for 50% S/D% (Fig. 4B). A larger region of low velocity can be observed in the ventricle upwards of the outlet channel. In the case the heart rate changes (Fig. 4C) at a steady value of S/D% in the ejection phase, these differences are very distinct.

A more uniform distribution was obtained for a higher heart rate HR 60 (Fig. 4D). At HR 30, lower velocity occurs in a larger part of the ventricle, however, this velocity does not result in clots. Figure 5 present an influence of the heart rate and S/D% on formation of stagnation areas. Stagnation areas are defined as a percentage of the area with the velocity lower than 0.01 m/s to the total area observed for the given cross-section.

The effect of S/D% is not considerable but differences in the parameter under analysis do not exceed 25%. From the diagram presented in Figure 5A, it can be seen that for the VAD operation parameters HR 50 and S/D% 40%, a percentage of the stagnation area is 23% lower than for HR 50 and S/D% 45%. In the case of HR 50 and 60, stagnation areas are approxiately 50% lower for the ejection phase than for the

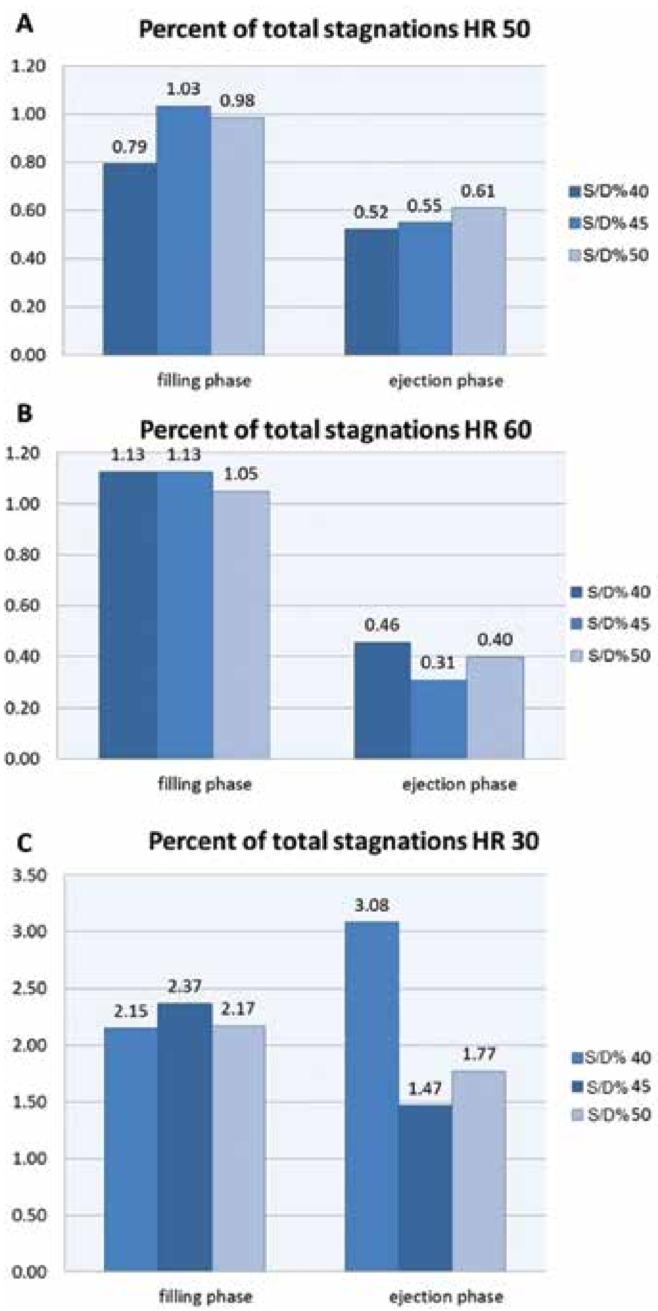

Fig. 5 - PED45, percent of total stagnations for the following parameters: S/D% 40, S/D% 45 and S/D% 50 and (**A**) HR 50, (**B**) HR 60, (**C**) HR 30.

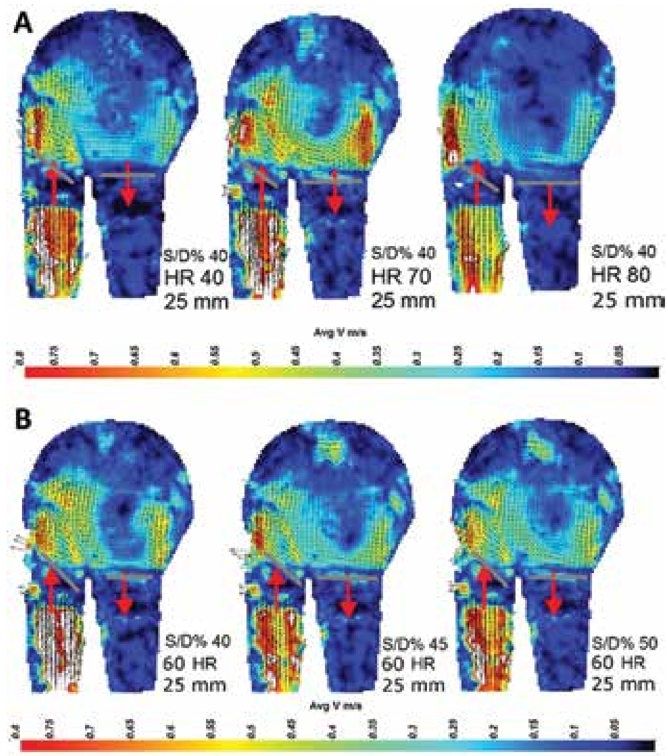

Fig. 6 - PED30: (**A**) a flow comparison for different heart rates at S/D% 40; (**B**) a flow comparison for different systole to diastole percentages at HR 60.

filling phase. The stagnation area in the filling phase is 2.3 times higher for the heart rate HR 30 than for HR 50 of the VAD area.

In the ejection phase, the stagnation area is 10 times larger for HR 30 than for HR 60 of the VAD area. For the heart rates HR 30 and 40, significant differences in stagnations areas in the ejection phase, even up to 100%, occur. In Figure 6, velocity distributions for the PED 30 VAD are presented. Changes in S/D% do not exert any significant influence on the operation of the VAD, but a higher value of S/D% decreases the stagnation area (Fig. 6B). A change in the heart rate, however, is a more significant parameter as it is responsible for an occurrence of undesirable high velocity differences. An increase in the heart rate (Fig. 6A), up to more than 70 beats per minute, caused a considerable increase in areas of low velocity in the central part of the VAD and a decrease of velocity in the inlet channel.

Conclusions

The PIV method allows for noninvasive observation of the flow field inside the VADs under investigation. Proper lighting of the seeded field is the key factor for obtaining correct images. In the experiment under analysis, mirrors were applied to light the inlet channel sufficiently at the side opposite the laser light source. As each optical measurement method, the PIV method is burdened with some limitations. In this instance, an application of disc valves obscured the inlet and outlet regions of the VAD, which resulted in falsely low velocity values in the region of valves on the images of velocity fields. Unfortunately, despite numerous trials with light beam reflection, this phenomenon could not be successfully eliminated. However, the inside of the VAD was illuminated adequately and reliable results of velocity fields pointing out to a circulating flow inside the VAD were attained. The flow, enforced by a type and location of disc valves, increases the circulation efficiency in the VAD, and thus decreases the region of low velocities.

The heart rate and S/D% changes exert an influence on the operation of heart valves and pediatric VADs. The results suggest that VAD operation deteriorates under higher heart rate values. Simultaneously, at 60, 70 beats per minute, higher values of S/D% – 45% or 50% – should be applied. This is followed by a decrease in the regions of lower velocity in the VAD. It has been also observed that for the heart rate of 80 beats per minute, the VAD membrane does not deform in a proper way. Thus, complete filling and ejecting does not take place in the VAD. The same procedure for measurements of PED 45 and PED 30 does not result in the same quality of measurements. Hence, this procedure requires further development and examination for PED 30.

Disclosures

Financial support: This work has been supported by the National Center for Research and Development, and performed in collaboration with the Foundation for Cardiac Surgery Development (FRK), Zabrze, Poland, Project No: PBS1/A7/1/2012.
Conflict of interest: None of the authors has financial interest related to this study to disclose.

References

1. Mozaffarian D, Benjamin EJ, Go AS, et al. Heart disease and stroke statistics—2015 update: a report from the American Heart Association. Circulation. 2015;131(4):e29–322.
2. Fraser CD Jr, Jaquiss RDB, Rosenthal DN, et al. Berlin Heart Study Investigators. Prospective trial of a pediatric ventricular assist device. N Engl J Med. 2012;367(6):532-541.
3. Drakos SG, Kfoury AG, Stehlik J, et al. Bridge to recovery: understanding the disconnect between clinical and biological outcomes. Circulation. 2012;126(2):230-241.
4. Kaczmarek I, Mair H, Groetzner J, et al. Mechanical circulatory support in infants and adults with the MEDOS/HIA assist device. Artif Organs. 2005;29(10):857-860.
5. Cabrera AG, Sundareswaran KS, Samayoa AX, et al. Outcomes of pediatric patients supported by the HeartMate II left ventricular assist device in the United States. J Heart Lung Transplant. 2013;32(11):1107-1113.
6. Reinhartz O, Hill JD, Al-Khaldi A, Pelletier MP, Robbins RC, Farrar DJ. Thoratec ventricular assist devices in pediatric patients: update on clinical results. ASAIO J. 2005;51(5):501-503.
7. Kilic A, Nolan TD, Li T, et al. Early in vivo experience with the pediatric Jarvik 2000 heart. ASAIO J. 2007;53(3):374-378.
8. Roszelle BN, Cooper BT, Long TC, Deutsch S, Manning KB. The 12 cc Penn State pulsatile pediatric ventricular assist device: flow field observations at a reduced beat rate with application to weaning. ASAIO J. 2008;54(3):325-331.
9. Fuchs A, Netz H. Ventricular assist devices in pediatrics. Images Paediatr Cardiol. 2001;3(4):24-54.
10. Jóźwik K. Modelling of Blood Flows. Łódź: Lodz University of Technology 2013.
11. Jozwik K, Obidowski D. Numerical simulations of the blood flow through vertebral arteries. J Biomech. 2010;43(2):177-185.
12. Kustosz R, Jarosz A, Gawlikowski M, Kapis A, Gonsior M. Rola i perspektywy rozwoju polskich pneumatycznych pomp wspomagania serca na rynku protez serca. In: Kustosz R, Gonsior M, and Jarosz A, eds. Polskie protezy serca, opracowanie konstrukcji, badania kwalifikacyjne, przedkliniczne i kliniczne. Zabrze: Epigraf 2013;334-366. http://www.pwpss.pl/mono2/h11.pdf. Accessed June 16, 2017.
13. Obidowski D, Klosinski P, Reorowicz P, Jozwik K. Influence of an Artificial Valve Type on the Flow in the Ventricular Assist Device. In: Bamidis PD, Pallikarakis N, eds. XII Mediterranean Conference on Medical and Biological Engineering and Computing 2010. IFMBE Proceedings, vol 29. Berlin, Heidelberg: Springer 2010;410-413.
14. Moll J. Artificial Heart Valve. United States Patent No 4,725,275; 1988.
15. Obidowski D, Klosinski P, Reorowicz P, Jozwik K. Influence of an Artificial Valve Type on the Flow in the Ventricular Assist Device. MEDICON 2010. IFMBE Proc. 2010;29:410-413.
16. Reorowicz P, Obidowski D, Klosinski P, Jozwik K. Flow Modelling in the Pneumatic Ventricular Assist Device with Mesh Deformation and Immersed Body Techniques-Investigation of Stagnation Zones. In: Jobbágy, Ákos, ed. 5th European Conference of the International Federation for Medical and Biological Engineering. New York: Springer. 2012;493-496.
17. LaVision. Product Manual for FlowMaster Getting Started. http://www.lavision.de/en/download.php?id=317. Accessed June 16, 2017.
18. Jodko D, Obidowski D, Reorowicz P, Kłosiński P, Jóźwik K. Angular Position Determination of Heart Valves in the Paediatric Ventricular Assist Device with Use of Computational Fluid Dynamics. Aktualne Problemy Biomechaniki. 2014;8:57-62.