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HYDRODYNAMIC PERFORMANCE OF A NOVEL SUTURELESSPROSTHETIC AORTIC VALVE

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The aim of the study was an in vitro hydrodynamic study of the developed prosthetic heart valve of the second generation, designed to carry out an implantation using "valve-in-valve" method. **Material and methods.** Prototypes of the developed prosthesis were studied under simulated physiological conditions of the heart using a Vivitro Labs pulse duplicator (Canada) in a comparative aspect with "UniLine" clinical commercial aortic valve bioprosthesis (Russia). Samples were tested by simulating sutureless implantation procedure. **Results.** The developed valves showed satisfactory hydrodynamic characteristics – for all cases of "implantation" from the position of the average trans-prosthetic gradient (6.1–11.1 mm Hg) and the effective orifice area (1.60–1.81 cm^2). The analysis of the regurgitation fraction allowed us to determine the optimal sizes for implantation using "valve-in-valve" method, which subsequently will form the basis of sizing guidelines for size selection. A qualitative analysis of the leaflet's work demonstrated the presence of slight asymmetry for a number of prostheses – in case of mismatch of sizes when simulating "valve-in-valve" procedure. **Conclusion.** The tests demonstrate the viability of the developed design from the standpoint of hydrodynamic efficiency and determines the basic rules of selecting a prosthesis for reimplantation relative to the primary valve.

Keywords: hydrodynamic efficiency, aortic valve prosthesis, trans-prosthetic gradient, effective orifice area.

INTRODUCTION

In Russia, the number of procedures for implanting heart valves bioprostheses is increasing, exceeding 2000 units/year [1]. However, in contrast to the existing advantages of bioprostheses associated with more sparing antithrombotic therapy, there is a need for repeated interventions resulting from the dysfunction development. It has been shown that the period of freedom from reoperation is 7.8 years on average [2–4]. The Valve-in-Valve Registry reports the global results of clinical use of bioprostheses of higher duration, i.e. 9 years [5, 6]. However, in general, the period can be considered short compared to mechanical prostheses. At the same time, it was shown that re-intervention is associated with a higher complications risk, and most importantly, increased mortality of up to 11.5% [1, 7, 8], due to the volume and duration due to the need to remove the dysfunction prosthesis and its subsequent replacement. to a "new" one by reprosthetics. Such aspects may limit the scope of the bioprostheses use due to some degree of leveling the advantages of valves based on biological materials. Considering the annual growth in the number of heart valve replacement surgery, the search for solutions to the problems of repeated interventions remains an urgent research task in the field of cardiac surgery in terms of the development of new constructions. A possible solution could be transcatheter prostheses, the experience of which with prosthesis-to-prosthesis implantation demonstrates satisfactory clinical results [9]. However, such specific limitations as higher cost, required qualification of the operating team and its equipment, the impossibility of direct access to the implantation site for excision of calcifications, as well as specific complications [10] do not allow this technology to enter the routine practice of heart valve replacement [11].

The Research Institute for Complex Issues of Cardiovascular Diseases develops a minimally invasive sutureless heart valve prosthesis intended for repeated interventions and installed as a "prosthesis to prosthesis" [12]. In this approach, there is no need for complete removal of the prosthesis with developed dysfunction and reapplication of fixing sutures on the "new" one, which allows to reduce the volume of the surgical wound in the area of the aortic root and the time of its clamping. On the other hand, open access to the operating site provides the partial excision of affected tissue with massive calcification and / or pannus. The main functional feature of the developed heart valve prosthesis from the point of view of its efficiency, safety and, ultimately, long-term results of reprosthetics lies in the hydrodynamic parameters of the structure [13]. Besides, the peculiarity of prosthesis-to-prosthesis implantation creates constructive stenosis, i.e. a deliberate decrease in the geometric area of the orifice due to the "new frame + old frame" design imposes increased requirements on hydrodynamics (Fig. 1, e). Considering the factors described above, the development focused on this very characteristic, the assessment of the hydrodynamic characteristics of the

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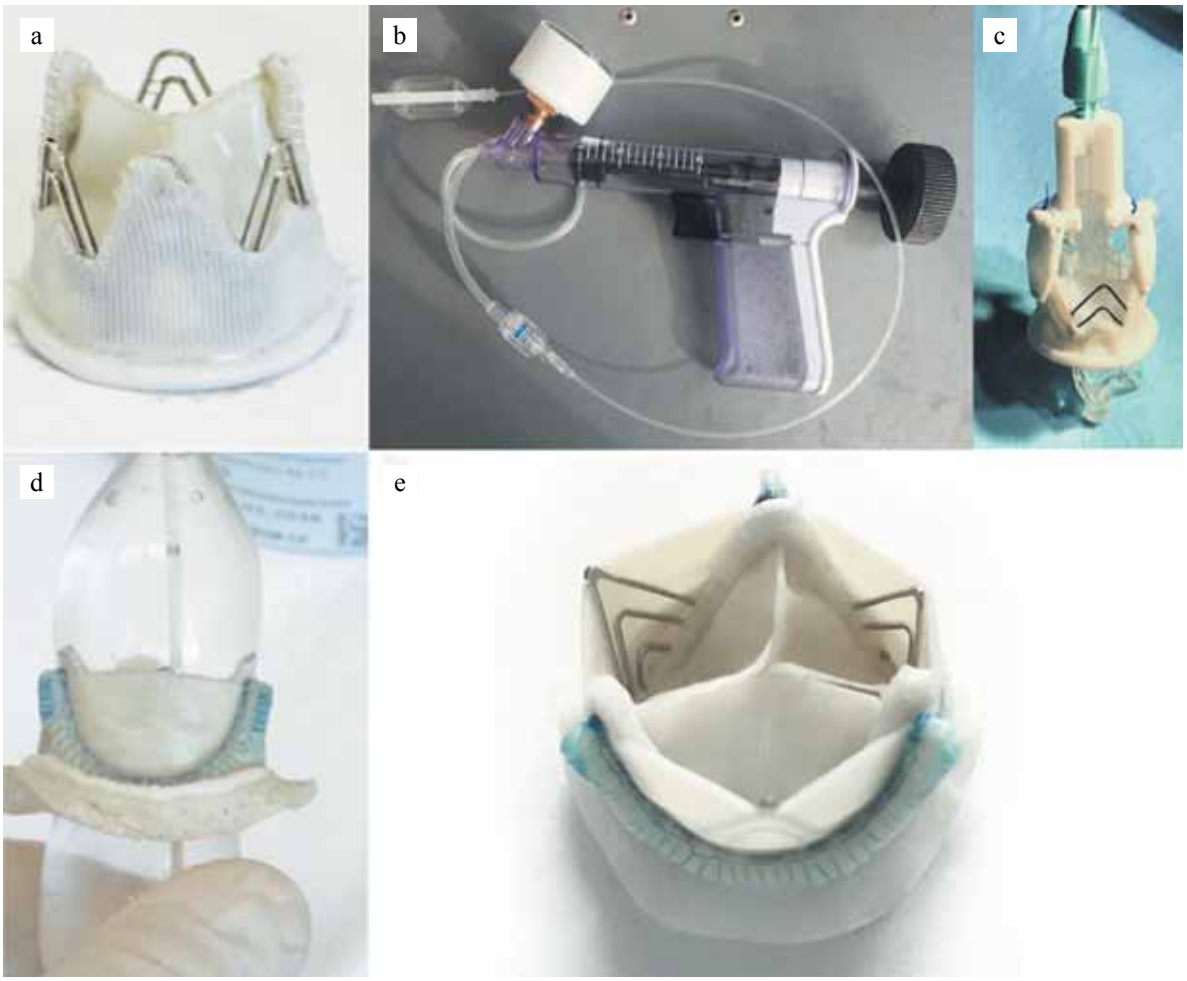

Fig. 1. Material and methods: a – design of the developed prosthesis; b – a delivery system comprising a balloon catheter and a high pressure syringe-defuser; c – re-implantation system with holder; d – the result of "valve-in-valve" implantation immediately after balloon dilation; e – the same, in the final state before the hydrodynamic study

experimental prosthesis under conditions of simulation of the prosthesis-to-prosthesis procedure.

MATERIALS AND METHODS

Prosthesis

From the point of design, the prosthesis under development is a mesh stent-like structure made of stainless steel, where the main components are mounted, i.e. a synthetic casing and a biological xenopericardial valve device stabilized with ethylene glycol diglycidyl ether with additional anticalcium treatment. The design of the supporting frame based on bar elements (stent) allows changing the outer diameter from preimplantation (15 mm) to target (17–21 mm) depending on the diameter of the prosthesis for reoperation. The use of medical grade stainless steel (AISI 316LVM) provides satisfactory biocompatibility even for "bare" elements of the support frame and maintains the final geometry at the target site [14]. Outside, the prosthesis is covered with a synthetic covering which turns into a single-row cuff made of a similar material. Both components ensure the sealing of the contact point of the two prostheses to reduce the risk of paraprosthetic fistula (Fig. 1, a). The device is implanted without sutures using balloon technology into the supporting frame of a failed heart valve prosthesis of the "prosthesis-to-prosthesis" type by connecting a high-pressure syringe to the catheter (Fig. 1, b).

Study methods

Considering the prosthesis is intended for prosthesis-to-prosthesis implantation, the study of its hydrodynamic efficiency was performed in two successive stages.

1. Study of the hydrodynamic parameters of the original "primary" prosthesis. For this, 3 clinical frame bioprostheses UniLine (CJSC NeoCor, Russia) were used, of 21, 23 and 25 standard sizes (TP), intended for clinical use in the aortic position. The prostheses consist of a rigid polymer support frame with mounted cusp and sheathing of biological material – cattle xenopericardium preserved with diglycidyl ether of ethylene glycol (DEE). The prosthesis involves suture installation; therefore, a biological sewing cuff is located at the base of the supporting frame (Fig. 1, b).

2. Study of the prosthesis under development. At this stage, the studied prosthesis of the corresponding diameter was "implanted" into the UniLine bioprostheses studied at the previous stage. For "implantation", a valvuloplasty balloon of our own design was used at a pressure of 4 atm with a syringe indeflator (Fig. 1, b). For each standard size of the original UniLine prosthesis, two variants of the studied prostheses were used, conventionally designated as -2TP and TP3. The stent-like mesh frame does not have a final standard size due to the design features; however, the valve device mounted on it provides tight locking only for a certain diameter of the "new" prosthesis. Thus, the prototypes of prostheses were created with two variants of the folding device for each UniLine standard size (21, 23, 25). The current stage of the study has made it possible to evaluate the most suitable standard size for implantation.

Hydrodynamic parameters were assessed with the Vivitro Labs (Canada) pulsating flow device at simulation of the heart physiological mode for 10 cycles in a steady state:

a) "beats" of the chamber simulating ventricle – 70 bpm;
b) pressure in the chamber simulating aorta – 120/80 mm Hg;
c) mean pressure in the chamber simulating aorta – 100 mm Hg;
d) minute volume – 5 l;
e) duration of systole – 35% cycle.

In the study, we assessed:

a) mean transprosthestic gradient as averaged over 10 work cycles the pressure difference "before" and "after" the bioprosthesis, measured using appropriate sensors in the chambers simulating the ventricle and aorta;
b) effective orifice area as the passage orifice area obtained from pressure and flow data by the formula (1):

$$EOA = 1{,}94 \sqrt{\frac{\int_{t_2}^{t_1} (q(t))^2 dt}{\int_{t_2}^{t_1} \Delta p(t) dt}} \quad (1)$$

where $q(t)$ – volume flow, l/s; $\Delta p(t)$ – transprosthestic gradient, mm Hg; t_1 – direct flow start time, s; t_2 – direct flow stop time, s;

c) regurgitation volume as the volume of fluid passing through the valve prosthesis in the opposite direction;
в) additionally, to qualitatively assess the operation of the valve device, video recording of the functioning of the prostheses was performed with the FastVideo-250 high-speed camera (Russia), followed by image analysis for the maximum opening and closure states.

All the described parameters were recorded for UniLine bioprostheses ("Before") and after installation of the developed prosthesis ("After").

RESULTS

Quantitative parameters

The obtained quantitative parameters showed an increase in the average transprosthestic gradient for -3TP relative to the primary one by 11.03–27.32% (Fig. 2). In this case, the maximum growth was noted for the UniLine-23 mm: from 6.83 to 9.40 mm Hg (2.57 increase). On the other hand, for -2TP implantation, the average transprosthestic gradient decreased by 10.64–33.22%. The maximum decrease was observed for the UniLine-25 mm: from 9.47 to 7.11 mm Hg (2.36 decrease).

The effective orifice area (Fig. 2), a parameter featuring the operation of the prosthesis in general, changed insignificantly for all prostheses' combinations: an

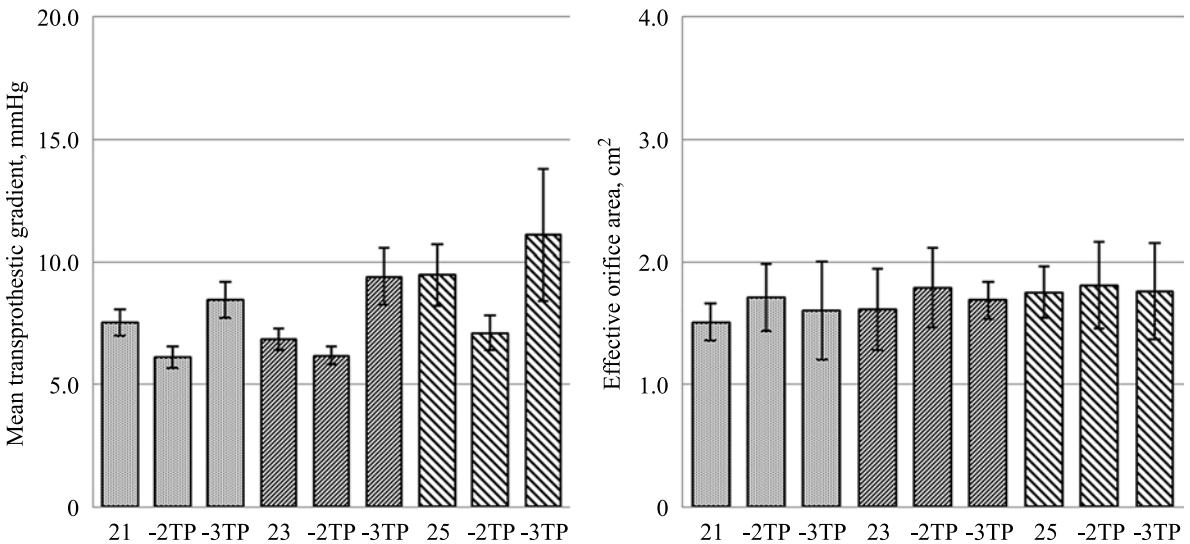

Fig. 2. Quantitative characteristics of the bioprostheses before and after implantation – average gradient and effective orifice area, grouped according to the initial standard sizes of "UniLine" prosthesis -21, 23, 25 mm. TP – size

increase by 0.40–11.70% relative to the primary one was recorded.

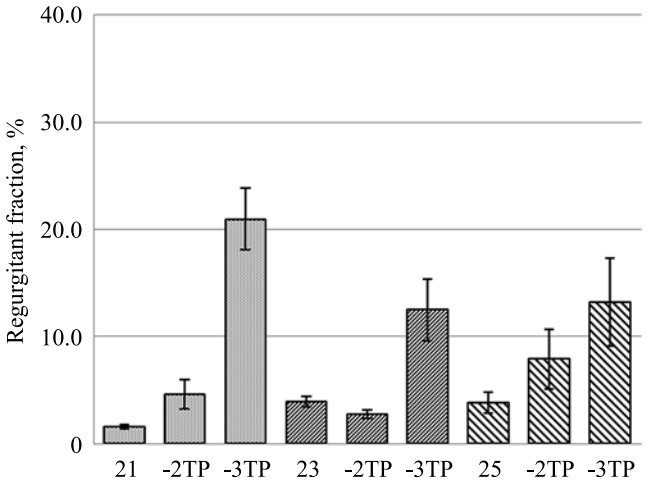

Fig. 3. The results of the assessment of the regurgitation fraction of the prostheses before and after "valve-in-valve" procedure. TP – size

The most notable parameter that changed after "prosthesis to prosthesis" implantation was the regurgitation fraction (Fig. 3). In all cases, the -3TP implantation option led to significant increase in this parameter in the most negative case (21 mm), 20.95% of the stroke volume accounted for the liquid reflux. The -2TP variant showed the best values of the regurgitation fraction in all cases (Fig. 3).

Qualitative assessment

The qualitative analysis of the prostheses performance before and after implantation showed a symmetrical, uniform opening of the cusp device. It was noted that for the -3TP, the closure state of the valves had greater symmetry and did not have such defects as twisting in the coaptation zone in comparison with the -2TP variant (Fig. 4). It is noteworthy that in the primary "Before" state, the UniLine bioprosthesis cusp has a slight barrel-like effect of the valves in the open state, while this was not observed for the experimental prosthesis.

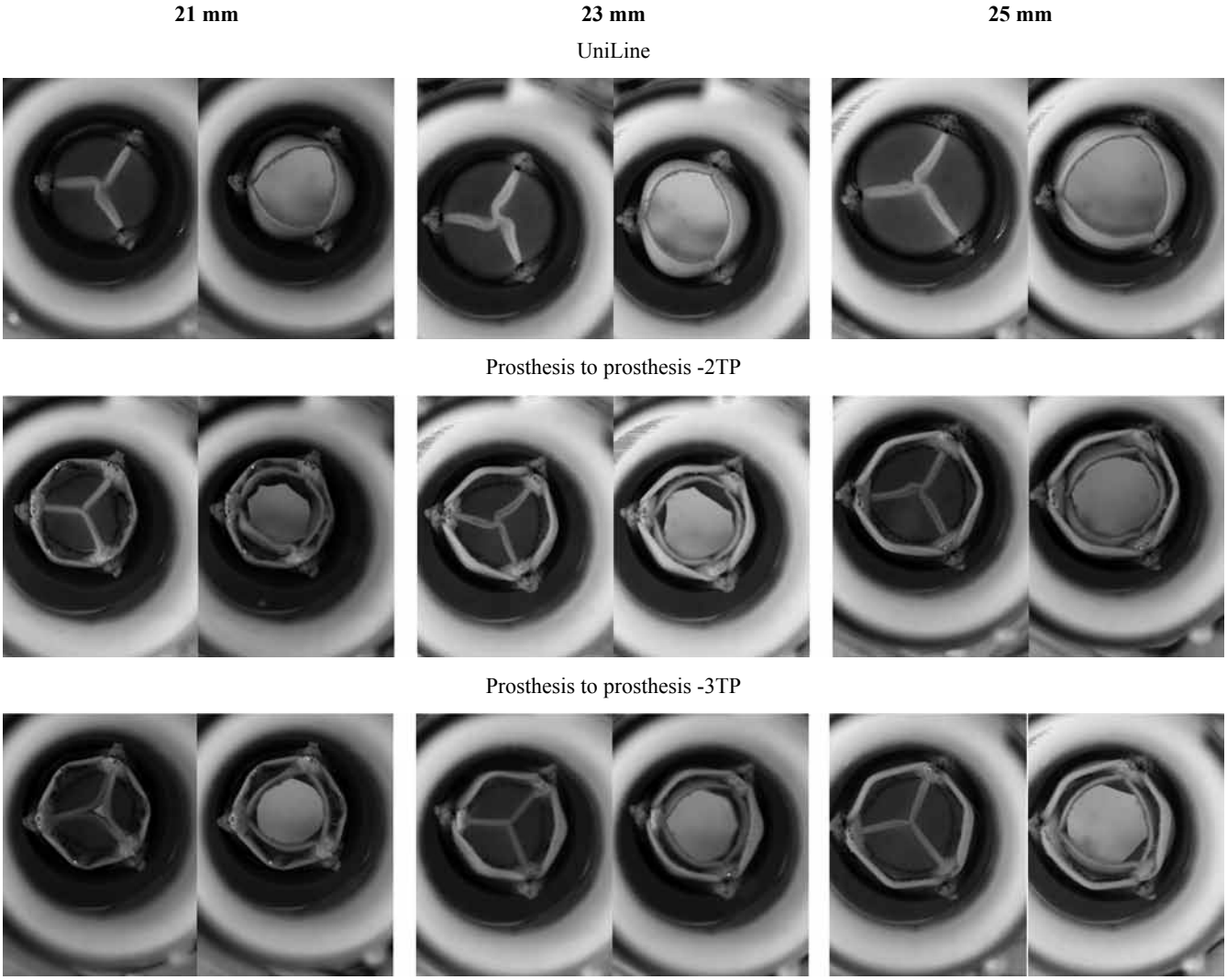

Fig. 4. Comparison of the quality work of the leaflet device before and after the implantation of the prosthesis for closed and open conditions. TP – size

DISCUSSION

The prosthesis under development shoes satisfactory hydrodynamic performance in terms of the transprothestic gradient, effective orifice area and regurgitation fraction in a comparative aspect relative to the original UniLine prostheses. It is noteworthy that with an adequate choice of the standard size of the experimental prosthesis, it is possible to achieve generally insignificant reductions in hydrodynamic efficiency. The supporting frame of the newly installed prosthesis has a nonzero thickness, narrowing the geometrical opening; at the same time, the higher efficiency of the experimental cusp device does not allow the flow parameters to change significantly, i.e. the effect of mutual compensation of negative "stenosing" and positive "productive" effects occurs. Th effect is presumably due to the use of a balloon-expandable stent-like design, which simulates the effect of balloon valvuloplasty, a significant increase in the lumen of the valve with dysfunction.

In this case, the issue of an adequate choice of standard size for reprosthetics (for UniLine bioprostheses) is caused by the need to simultaneously ensure maximum performance and safety of the valve for reprosthetics. The conducted study, on the one hand, shows the advantages of the -2TP option in terms of quantitative parameters; however, the quality -3TP valve device differs markedly in the positive sense. The analysis showed the presence of a slight asymmetry (twisting) of the closure state of the -2TP prostheses, which could potentially worsen over time due to the effect of biomaterial stretching [15, 16]. In the case of -3TP, the occurrence of a significant fraction of regurgitation (up to 20.95%) is due to insufficiently tight closure of the valves and thus, the formation of transvalvular regurgitation. In this variant, the above-described biomaterial stretching can lead to a positive effect: the leveling of high values of the regurgitation fraction by creating a tight closure of the coaptation zone without the effects of asymmetry of the valves. It is worth noting that the symmetry of the coaptation zone positively effects the prosthesis durability due to more even distribution of stress without the occurrence of local extreme values (stress concentration) [17, 18]. However, in the modern cardiac surgery practice, the intervention success is assessed immediately after the prosthesis is installed, and high values of the regurgitation will be regarded as failure of the dysfunction correction operation; therefore it is necessary to use a more "reliable" option, i.e. -2TP.

In general, the results obtained for both primary UniLine bioprostheses in comparison with frame valves, and experimental samples relative to transcatheter analogs are consistent with the literature data on studies of domestic and foreign prostheses. Thus, the hydrodynamic characteristics of the UniLine prostheses are comparable to those for Carpentier-Edwards PERIMOUNT and Medtronic Hancock® valves of similar standard sizes (21–25 mm) [19]: the average transprothestic gradient is 5.8–6.2 and 11.9–18, 1 mmHg with the effective orifice area 1.82–2.12 and 1.20–1.49 cm^2, respectively. Besides, the obtained results are in compliance with the clinical hemodynamic parameters of Medlab-KT which is principally similar to the domestic development (CJSC NPP MedInzh) which, nevertheless, is intended for transcatheter implantation – the average transprothestic gradient is 8.41 ± 4.21 mm Hg [20].

Another group of similar devices which the results of the present experiment are potentially necessary to be compared to are transcatheter prostheses used for "prosthesis-to-prosthesis" implantation, mainly Edwards Lifesciences SAPIEN and Medtronic CoreValve™ bioprostheses [21]. The transprothestic gradient according to the results of functional studies is shown to be 7.7–16.9 mm Hg which is slightly higher than the mean transprothestic gradient in primary transcatheter prosthetics: 0–10 mm Hg [20, 22, 23]. Nevertheless, these results are considered satisfactory in terms of clinical efficacy expressed in a decrease in the NYHA functional class [24].

CONCLUSION

The design of the prosthesis under development has shown its consistency in terms of functional characteristics, both in comparison with the original UniLine prosthesis and with literature data. However, the study demonstrated the need for careful selection of the appropriate valve size to minimize safety risks and dangers of significant reduction in hydrodynamic efficiency, considering the prosthesis-to-prosthesis implantation technique.

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The authors declare no conflict of interest.

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