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# Hemodynamic parameters within aortal stent-grafts vs. their spatial configuration – a comparison based on computer simulations

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## Summary

**Background:** It is difficult to find reliable premises which would enable a modification of the construction of stent-grafts to improve their durability and stability. Many systemic conditions make a comparison of homogeneous groups of operated patients a complicated task. Hence, it is helpful to use computer simulations and to verify them in a clinical observation. The hemodynamic parameters within aortal stent-grafts depending on their spatial configuration were compared using a computer simulation.

**Material/Methods:** Computer simulations were made for 6 patients with abdominal aortal aneurysm (AAA) in whom bifurcated aortal stent-grafts were implanted. A basis for a spatial model were angio-CT data. Flow rate parameters were obtained in US-CD. In numerical calculations, CFD - Fluent® 6.2 software was used. Numerical grids (about 300,000 tetrahedral elements) were generated on the basis of three-dimensional geometries of AAA segmented from CT scans. A laminar character of flow was assumed. Blood viscosity was described by Quemada's rheological model. In all patients, two variants of the graft geometry were generated assuming that common long-body and short-body grafts were applied. The patients' real anatomical conditions were taken for the simulations. Pressure drop on the graft level and wall shear stress were analyzed.

**Results:** It was found that the short-body graft caused a higher pressure drop along the inlet-outlet segment. The long-body graft offered smaller resistance to blood flow, and, consequently, the shear stress was lower. For the rate around 0.8 m/s, the difference reached 5500 Pa. In both variants, the highest value of shear stresses occurred near the bifurcation area.

**Conclusions:** An increase of the shear stress is more distinct when the short- body graft is used, which can suggest that this part of the graft should be as long as possible.

**Key words:** **Abdominal aortal aneurysm • endovascular therapy • stent-graft • CFD**

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## Background

Due to generally used ultrasonographic examinations, the number of detected abdominal aortal aneurysm (AAA) has grown recently [1]. The last decade is characterized also by a dynamic development of endovascular techniques used in AAA therapy. At present, stent-grafts are a well-known method of aneurysm therapy [1-4]. However, efforts are continued to improve both the procedure and process of qualification for surgery. There is an intensive debate on the advantages of stent-grafting over a classical operation [5-8]. It is difficult, however, to obtain relevant arguments without putting patients at risk of innovations. Hence, an idea has arisen to use calculation techniques in stent-graft designing and evaluation of results of the therapy [5, 7-11].

The aim of this study was to estimate the pressures which occurred in the aorta after stent-grafting on the basis of computer simulations and to determine changes of these parameters depending on spatial configuration of the graft.

## Materials and methods

Computer simulations were carried out in 6 patients with abdominal aortal aneurysms subjected to therapy by the endovascular method in the years 2004-2006. In all cases, Zenith® bifurcated stent-grafts (Cook) were implanted. The basis to formulate a 3D model of the aneurysm used in the simulations were the data obtained in angio-CT examinations, which is now a reference method for pre-operative diagnostics of aneurysms and their further observation after the applied treatment [1, 2, 12-14]. The examination was performed using a helical multislice systems (16 and 64 rows of detectors) after intravenous administration of 1 ml contrast medium/kg body weight at iodine concentration 350 mgI/ml. The examination covered vessels from the diaphragm to the inguinal ligaments. Input data were collected during 6 days to 7 weeks prior to the surgery, and the examination was repeated after implanting the stent-graft (3 to 24 months after the operation). The combined geometry of abdominal aortic aneurysms, especially those of curved neck and iliac arteries, can change after implantation. Since this has an effect on the distribution of pressure and hemodynamic parameters of flow, the cases of aneurysms without angulation in the vicinity of the neck and the aortic bifurcation were the only ones selected for analysis.

The data were processed into the layers of thickness not exceeding 5 mm written in the DICOM 3.0 format. A 3D vessels models were used as a domain of mathematical calculations. Numerical grids (about 300,000 tetrahedral elements) were generated on the basis of three-dimensional geometries of AAA and stent-grafts segmented from CT scans (Fig. 1). This ensured reliability of the simulations [5-8]. The shape of the vessel from the renal artery (inlet area) to the external iliac artery was taken into account in the model, which made us define inlet areas for each of them separately.

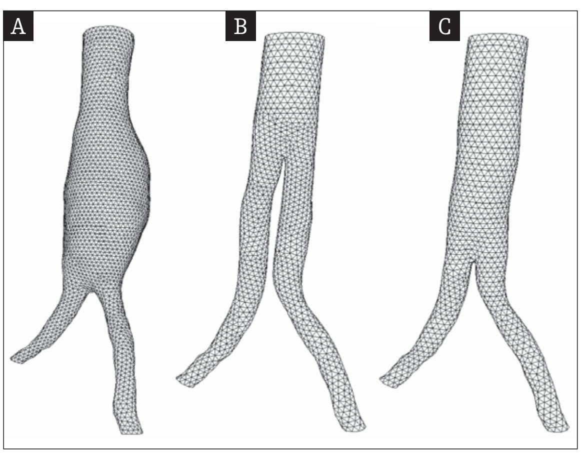


**Figure 1.** Three-dimensional computational grids of: **A**) AAA before operation, **B**) short body stent-graft, **C**) long body stent-graft.

Liquid flow rates in the vessels were obtained from the ultrasonographic examination (US-CD). A convex probe with frequency range from 3 to 5.5 MHz was used. The flow rate was recorded using the pulsating wave (PW) method at the level of the inlet region, within the neck of the aneurysm, or below the renal arteries. After stent-grafting, the flow rate was measured on the same level, in the common part of the graft. The measuring volume was situated in the central part of the vessel. Direction of the Doppler beam was tangential to the flow axis preserving the angle correction (<60%). A pulsating character of flow was represented by a time profile of maximum rates for both flow directions as a boundary condition at the inlet. For automation of the cyclic calculation process, the real blood flow rate distribution was described by Fourier series (12 elements) (Fig. 2). To standardize the flow resistance and shear stress calculations, average flow rates in the cardiac cycle calculated for the group were used.

In numerical calculations a commercial CFD - Fluent® 6.2 software (Fluent INC) was used. Constant value of blood pressure was set as a boundary condition at the outflow from renal vessels (this assumption was justified by the lack of important bifurcations along the aorta below the place where renal arteries branched off to the level of common iliac arteries, and after stent implantation covering the area to the external iliac arteries). Such configuration of the model enabled an extensive analysis of the effect of graft geometry on pressure drop during blood flow [9]. It was shown that a relatively big vessel diameter and high blood viscosity allowed us to assume that flow in the abdominal aorta was laminar [5-7]. In the project, preliminary calculations were made in which the determined Reynolds number that characterized the flow reached the value below 600 at the maximum flow rate. Hence, the assumption of laminar flow was made in the model. Blood viscosity was described by Quemada's rheological model which took into account non-Newtonian liquid properties [15]. Calculations were made in unsteady state. The algorithm of data acquisition and processing applied in the study was used by other researchers and its reliability was confirmed by numerous model experiments [5-8, 16].

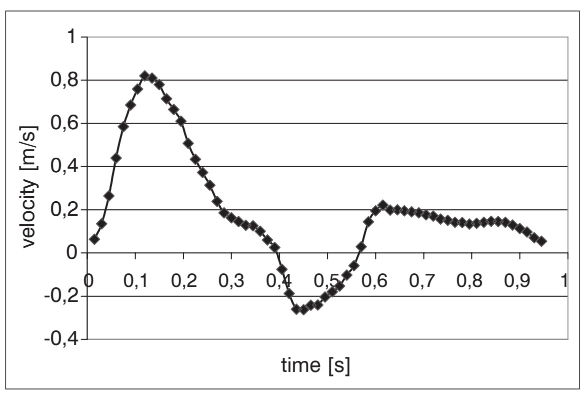


**Figure 2.** Blood flow velocity at the inlet.

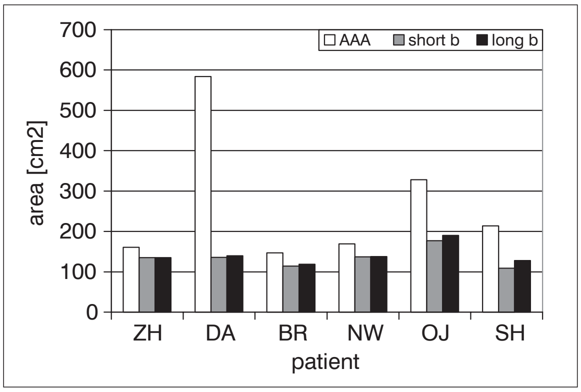


**Figure 3.** Wall surface (cm²) of the vessel in patients prior to and after grafting (two variants of the stent-graft configuration).

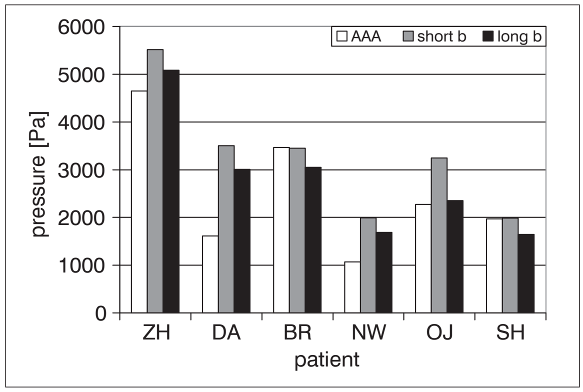


**Figure 4.** Pressure drop (Pa) on the abdominal aorta level in patients prior to and after grafting (two variants of the stent-graft configuration).

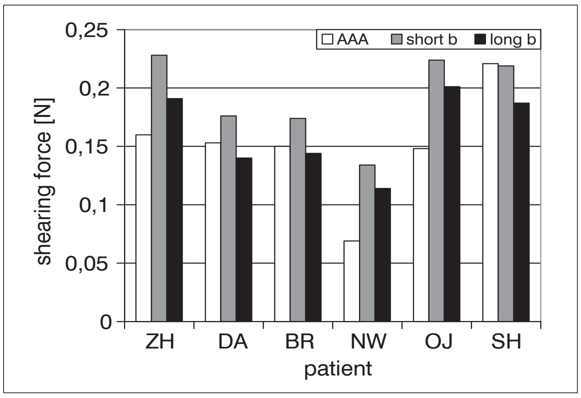


**Figure 5.** Total shearing force (N) on the abdominal aorta level in patients prior to and after grafting (two variants of the stent-graft configuration).

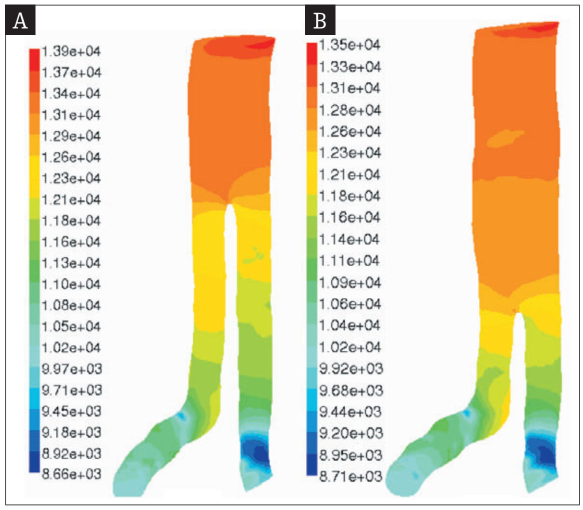


**Figure 6.** Blood pressure contours (Pa) in: **A**) short-body stent-graft, **B**) long-body stent-graft on the peak of myocardial contraction.

Taking advantage of mathematical capacity of the program and taking into account the information on the assortment of products, for all patients after the implantation, two stent-graft geometries were generated assuming that common long-body and short-body had been used. The simulations covered real anatomical conditions of each patient as well as the shape of his arteries and aimed at a comparison of hemodynamic conditions in both stent-graft types. The resistance of flow and wall shear stress were analyzed with reference to the state before and after implantation of both stent-graft variants. Shear stress profiles were compared for a maximum flow rate as they reflected distinct differences which resulted from the flow duct geometry.

## Results

The total wall surface of the flow duct calculated in the aneurysm prior to implantation depended on the length of the tested segment, the degree of aorta dilation and the presence of a thrombus. Extremely high values were recorded in the case of big aneurysms without a mural thrombus (0.0584 m²), and low ones in aneurysms with an extensive mural thrombus (0.0147 m²). The implantation of stent-grafts caused reduction of the flow duct surface to 0.0119-0.019 m² in the case of the long body stent-grafts and to 0.0109-0.0177 m² when the short-body stent-grafts were used (Fig. 3).

The resistance of flow, expressed by pressure drop, increased with a decrease of the flow duct surface. The lowest resistance, 1069 to 4647 Pa, was observed before the implantation. The applied short-body stent-grafts in the same flow conditions caused bigger pressure drop on the inlet-outlet segment. The long-body implant was less resistant to blood flow. In the case of the short-body stent-graft, the resistance increased to 1985-5517 Pa and it was 1644-5083 Pa in the case of implants with long body. At the flow rate about 0.8 m/s the difference reached 5500 Pa (Fig. 4).

The integrated shearing force on the wall surface in patients before grafting ranged from 0.069 to 0.21 N. In patients after the implantation of the short-body stent-graft it was between 0.13 and 0.23 N, while in the long body variant from 0.11 to 0.2 N (Fig. 5). In both variants of the stent-graft, the highest pressure gradient was observed near the place of bifurcation (Fig. 6a, 6b). Lower values of the elevated shear stress in the case of long bodies gave evidence of smaller blood flow resistance in this stent-graft type. Details referring to wall surface, flow resistance and shearing force are presented in Table I.

**Table I.** Parameters calculated from simulations for maximum flow rates in the aorta (on the peak of myocardial contraction).

| Symbol | Parameter | Before operation | Short body | Long body |
|---|---|---|---|---|
| ZH | Wall area, m2 | 0.0161 | 0.0135 | 0.0134 |
| | Pressure drop, Pa | 4647 | 5517 | 5083 |
| | **Total shearing force, N** | **0.161** | **0.231** | **0.192** |
| DA | Wall area, m2 | 0.0584 | 0.0136 | 0.0140 |
| | Pressure drop, Pa | 1611 | 3501 | 3090 |
| | **Total shearing force, N** | **0.153** | **0.176** | **0.14** |
| BR | Wall area, m2 | 0.0147 | 0.0113 | 0.0119 |
| | Pressure drop, Pa | 3464 | 3452 | 3049 |
| | **Total shearing force, N** | **0.151** | **0.17** | **0.144** |
| NW | Wall area, m2 | 0.0169 | 0.0137 | 0.0138 |
| | Pressure drop, Pa | 1069 | 1990 | 1689 |
| | **Total shearing force, N** | **0.069** | **0.134** | **0.114** |
| OJ | Wall area, m2 | 0.0328 | 0.0177 | 0.0190 |
| | Pressure drop, Pa | 2272 | 3246 | 2553 |
| | **Total shearing force, N** | **0.148** | **0.224** | **0.197** |
| SH | Wall area, m2 | 0.0214 | 0.0109 | 0.0128 |
| | Pressure drop, Pa | 1968 | 1985 | 1644 |
| | **Total shearing force, N** | **0.211** | **0.219** | **0.187** |

## Discussion

It is extremely difficult to formulate reliable assumptions which would enable modification of the construction of stent-grafts, especially in view of their durability and location stability. It is a complicated task to obtain a homogeneous group for investigations because of a number of independent systemic conditions which have an effect on the patient's survival, implant patency and which hinder inference backed up by statistical evidence [1, 5, 14, 17, 18]. Hence, there is a strong tendency to formulate hypotheses on the basis of computer simulations and their subsequent verification in clinical conditions [5, 8, 19]. Despite many restrictions which are a result of problems in representing circulating blood properties, suitability of computer simulations with the use of the data collected in imaging examinations (CT and US) was confirmed in a number of experimental studies [8, 9]. The program used in the present study is most widely applied in the literature and the assumed method of spatial grid construction and its resolution, as well as the proposed algorithm of the mathematical data analysis, guarantee reliability of further computations [5, 7].

The data obtained before and after the implantation of intravascular stent-graft show clearly a change in the hemodynamic conditions in the form of a bottleneck in the flow duct which is advantageous for static pressure reduction, particularly in the place of the biggest extension. On the other hand, the values of shear stress increase [7, 9, 16]. The obtained results are consistent with theoretical data and the observations of other authors with regard to implants located in aorta (Feauenfelder, Juchems, Liffman, Sutalo) and peripheral arteries (LaDisa) [5, 7, 8, 10, 17].

The integrated shearing force being calculated on the wall surface is a sum of product of local value of the shear stress on the wall of a blood vessel or implant as an element adjacent to the calculation domain boundary. Its value represents the force acting on the stent-graft in the blood flow direction [7, 9]. It is assumed that the stresses concentrating near the bifurcation which generate breaking force on the level of proximal fixation are of key importance for the stent-graft migration [6, 7, 9, 20]. A comparison of different implant geometries enables us to estimate the effect of changes in flow conditions on the value of stresses formed in the region of proximal fixation which have an influence on its stable location [6, 20]. The obtained results confirm an increase of shear stress near the bifurcation, especially when the short-body stent-graft is used. It can be suggested that, if anatomical conditions allow, this part of the stent-graft should be as long as possible, as far as it does not have an influence on the bend of flow stream direction. The bends of stent-graft arms, especially with their segment-like structure, may cause flow disturbances which contribute to the implant clotting and an increased resistance at the stent-graft level [3, 4]. This issue is complicated and further analysis requires ascertaining how WSS is formed in cases of aneurysms with angulation of the neck and iliac arteries, which reduce flow and cause turbulence. It will also be important to examine implants in cases of non-symmetrical bifurcation. Observations are necessary to find out to what extent changes of flow in the arms or bottlenecks below the implant can affect stability of the stent-graft fixation. Development of precise recommendations for correct location of the stent-graft or arterioplasty below the implant would be a great advantage of computer simulations.

## Conclusions

1. The values of shear stress are much higher when the short body stent-graft is applied.

2. It seems that common part of the graft should be as long as possible so that it does not change the outflow direction below the graft.

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