In Vitro Evaluation of Upstream and Downstream Influences on Blood Pressure of the Hybrid Treatment of Thoracoabdominal Aortic Aneurysms

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Background: The aim of our study was to assess, by means of an experimental model, whether different geometries in retrograde bypass and stent-graft deployment may affect upstream and downstream blood pressure in hybrid treatment.

Methods: An in vitro model of the arterial circulation has been prepared, which consists of a peristaltic pump, silicon tubes with geometrical and mechanical properties close to realistic arteries, a terminal reservoir kept at constant pressure, and a sequence of pressure transducers. The system allows us to study the pressure wave propagation in physiological conditions and simulate the patient's conditions as a result of debranching in 2 different configurations.

Results: In configuration 1, the mean pressure value (Kpa) was 4.72 in silicone tube before stent graft and debranching, 4.59 in visceral and renal bypass, and 4.38 in silicone tube after stent graft and debranching. In configuration 2, the mean pressure value (Kpa) was 5.22 in silicone tube before stent graft and debranching, 4.48 in visceral and renal bypass, and 4.99 in silicone tube after stent graft and debranching.

Conclusion: The experimental data suggest that the debranching geometry and the material of the grafts and stent grafts change significantly the physiological arterial pressure possibly leading to an augmented pressure upstream of the stent grafts, owing to retrograde pressure waves toward the heart, and a decreased pressure downstream visceral and renal arteries.

INTRODUCTION

Hybrid treatment was proposed for the first time in 1999.[1] This treatment consists in 2 steps: first, a retrograde revascularization of visceral and renal vessels, followed by an exclusion of the aneurysmal sac through the placement of a stent graft.

According to some authors, hybrid treatment should be reserved for high-risk patients in selected cases.[2] Despite some advantages in literature compared with open repair, mortality and complication rate remain high.[3]

One of the key points of hybrid treatment is retrograde bypass. Cumulative patency of retrograde bypass is good, but there are no specific data on how best to achieve the bypass.[4] The main factor that influences how to perform the retrograde bypass is the location chosen for the proximal anastomosis. Consensus suggests that either the infrarenal aorta or the iliac arteries should be chosen.

The aim of our study was to assess, by means of an experimental model, whether different geometries

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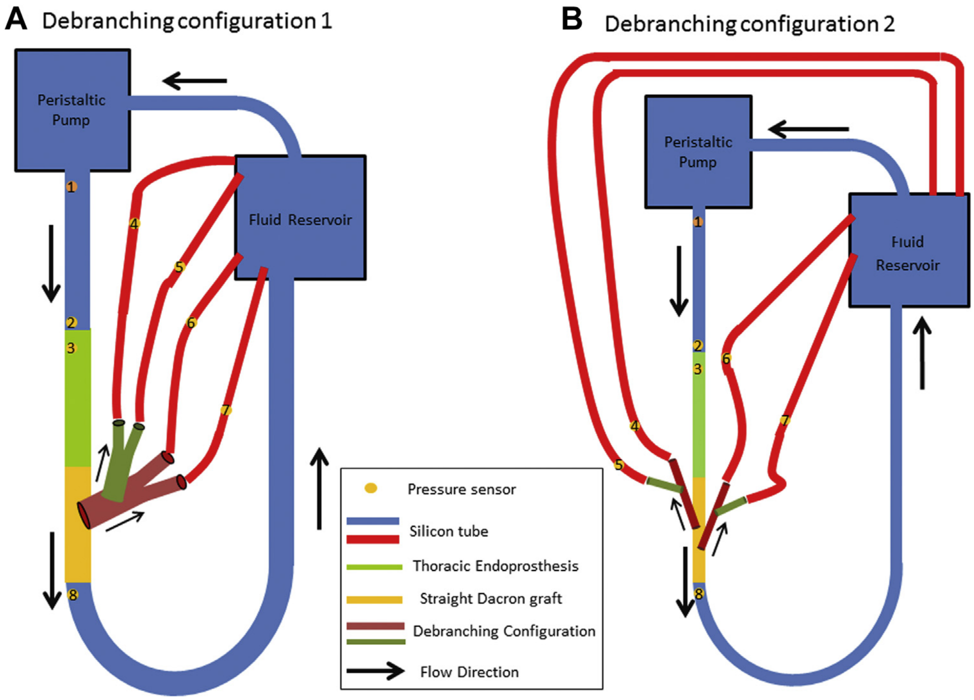

Fig. 1. Sketch of the 2 debranching configurations: **(A)** configuration C1 and **(B)** configuration C2.

in retrograde bypass and stent-graft deployment may affect upstream and downstream blood pressure in hybrid treatment. Our second objective was to verify whether hybrid treatment might have central hemodynamic repercussions.

METHODS

The experimental measurements described hereafter were made by means of a closed-circuit physical model of the hemodynamics within the arterial system. In particular, 2 different models (Dacron® bypass for celiac trunk, superior mesenteric artery, and both renal arteries) were used to study the role of different configurations of hybrid implants.

Type of Debranching

Configuration C1. C-TAG stent grafts (30 mm diameter and 100 mm length) (W. L. Gore & Associates, Inc., Flagstaff, AZ), straight Dacron bypass (diameter 26 mm). A bifurcated Dacron graft (16 × 8 mm) was used to obtain a bypass from the straight Dacron to both renal arteries (renal bypass). Visceral artery revascularization was performed from the main body of the aortorenal bypass to the origin of the celiac trunk and superior mesenteric artery with a bifurcated 14 × 7 mm Dacron graft (visceral bypass).

Configuration C2. C-TAG stent grafts (30 mm diameter and 100 mm length) (W. L. Gore & Associates, Inc.), straight Dacron bypass (diameter 26 mm). A double straight Dacron graft (8 mm) was used to obtain a bypass from the straight Dacron to the renal artery (renal bypass). Visceral artery revascularization was performed from the straight Dacron graft to the origin of the celiac trunk and superior mesenteric artery with a straight Dacron graft (7 mm) (visceral bypass).

A sketch of the 2 configurations tested is reported in Figure 1.

A Saint-Gobain Sani-Tech STHT-C-1000-1 silicone tube was used to model the descending tract of the aorta. This tube has an internal diameter d_I = 25.4 mm and an external diameter d_E = 26.9 mm. The silicone has a constant tensile modulus of 2.103 MPa and a hardness value of 50 SH − A. A valve connected to the aortic inlet prevents backward flow from the silicone tube. The straight graft is a knitted Dacron (PET fiber) graft and has a constant diameter of 2.54 cm and a wall thickness of 0.35 mm. A specimen of the graft was taken to evaluate the complex modulus.

A Watson-Marlow 620U peristaltic pump (PP) was used to reproduce the action of the left heart.

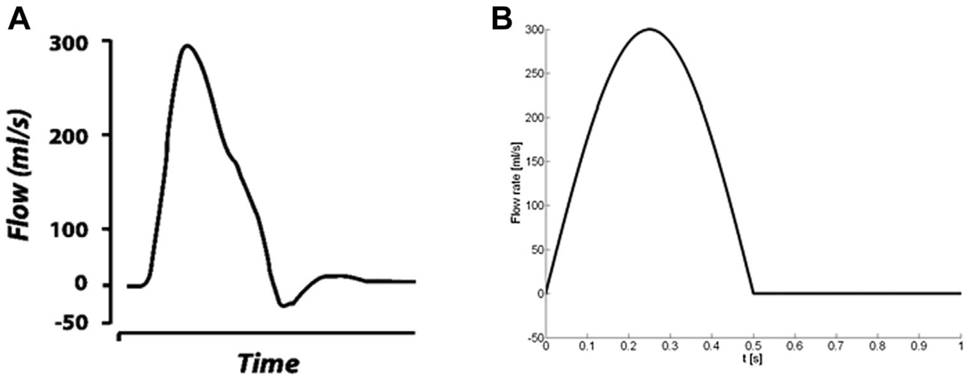

Fig. 2. Comparison between the physiological input flow rate **(A)** and the semi-sinusoidal one we used in our experiments **(B)**.

The pump is controlled remotely by a data acquisition system (DAQ). The flow wave is a simplified version of the cardiac signal. The systolic portion of the cardiac cycle is approximated with a semi-sinusoidal flow wave generated by the PP, whereas the diastolic portion is assumed to be characterized by null inflow. A comparison between the physiological input flow and the one used for the artificial aortic circulation is shown in Figure 2. The actual flow rate is measured at the aortic inlet by means of an OPTIFLUX 5000 magnetic flowmeter. The tube is filled with distilled water, which is used to model blood flow. The density and viscosity of distilled water are similar to those of blood: density $\rho = 1000\ kg/m^3$ and cinematic viscosity $\nu = 10^{-6}\ m^2/s$ for water, $\rho = 1000\ kg/m^3$ and $\nu = 3 \times 10^{-6}\ m^2/s$ for blood.

Eight Honeywell 26PCA strain gauge pressure sensors (pressure range 0−1 psi) with a nominal sensitivity of 23 mV/psi and an excitation voltage of 10 V were used in the experiments. The acquisition frequency was set at 1 KHz to accurately reproduce the pressure waves. The acquisition of all the signals was performed using the DAQ system. The locations of the pressure sensors along the vessel and the prostheses, for the 2 different configurations, are shown in Figure 1.

A valve is placed at the end of the silicone tube to induce concentrated pressure losses that model the systemic resistances due to arteries, arterioles, and capillaries. At the end of the circuitry, a closed fluid reservoir is placed. The overflow reservoir has the double aim of providing fluid for the pulsatile pump and modeling the venous system by imposing a static pressure equal to 4 Kpa, sufficient to avoid spurious vessel collapse. The terminal part of the silicone tube is connected to the PP, then the system is a closed loop and lies horizontally on a soft-surface bench, to reduce the vibrations and to allow the silicone tube to deform isotropically.

RESULTS

In Figure 3, the pressure waves measured for the 2 different configurations are shown. The 3 different lines refer to the measurements performed at 3 different locations: on the silicone tube next to the straight graft (sensor 2), on the renal bypass (sensors 6−7 C1 configuration and sensors 4−6 C2 configuration) and visceral bypass (sensors 4−5 C1 configuration and sensors 5−7 C2 configuration), and on the silicone tube next to the Dacron graft (sensor 8). The values refer to the percentage ratio between the pressure minus the hydrostatic pressure and the average value of the pressure peak measured by the sensor located on the silicone tube next to the straight graft (sensor 2) minus the hydrostatic pressure.

In Table I, mean pressure value related to C1 and C2 in different locations are reported.

We noticed that in both cases the pressure waves were significantly attenuated after passing inside the hybrid implant. In the case of C1, the pressure peak at the outlet of the implant is about 80% of the peak measured in the silicone tube before the implant. In the case of C2, the peak pressure at the outlet of the implant is only about 40% of the peak measured at the inlet of the implant. The greater attenuation of the pressure wave found for configuration C2 may also be observed in Figure 4, where the comparison between the pressure waves recorded by sensor 2 in the 2 configurations is shown.

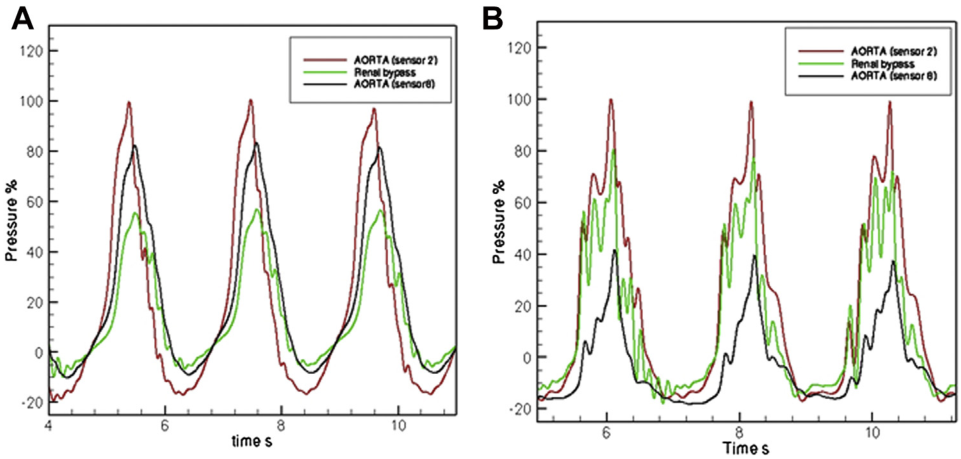

Fig. 3. Normalized pressure wave measured in 3 different locations for the 2 different configurations: **(A)** configuration C1 and **(B)** configuration C2.

Table I. Mean pressure value (Kpa) in different sites

	Mean pressure value (Kpa)	
Sensor localization	Configuration 1	Configuration 2
Sensor 1	4.72	5.22
Sensors 4–7	4.59	4.48
Sensor 8	4.38	4.99

Sensor 1, silicone tube before stent graft and debranching; sensors 4–7, visceral and renal bypass; sensor 8, silicone tube after stent graft and debranching.

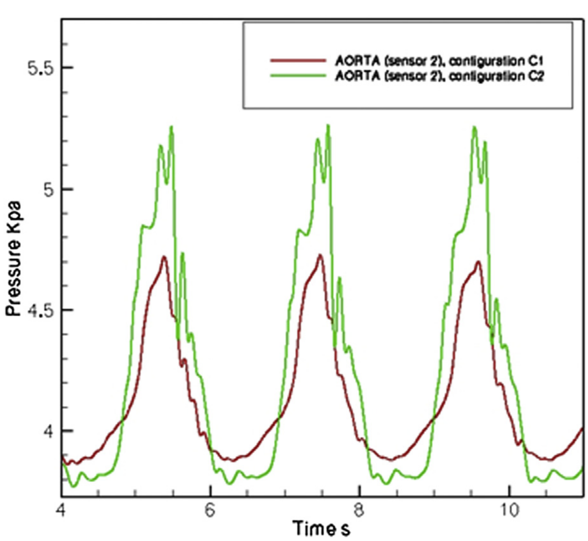

Fig. 4. Pressure wave measured at the inlet of the implant for the 2 different configurations. Configuration C1, red *line*; configuration C2, green *line*.

The larger values of the maximum pressure at the implant inlet found for C2 have to be considered as an augmented reflection of the incident pressure wave due to the different geometrical structure of the implant.

A difference in pressure wave attenuation for the 2 configurations is also found in the renal bypasses. For the C1 configuration, the pressure peak in the renal bypass is about 55% of the peak measured in the silicone tube at the inlet of the implant, while for the C2 configuration, the pressure peak in the renal bypass is about 80% of the peak measured at the inlet of the implant. This difference can also be observed in Figure 5, where the comparison between the pressure waves inside the renal bypass for the 2 different configurations is shown (sensors 4 and 5 in C1 and sensors 5 and 7 in C2).

DISCUSSION

Our study was designed to determine whether the retrograde bypass performed with various geometries in the hybrid treatment of thoracoabdominal aneurysms may have hemodynamic effects. All our results were obtained from an experimental model.

Our study successfully demonstrated for the first time a difference between upstream and downstream pressure values in visceral and renal artery bypass: the pressure is attenuated in the bypass. Clinically, this pressure drop does not seem to affect bypass patency, and it is different depending on the geometry of the bypass. Literature data do not

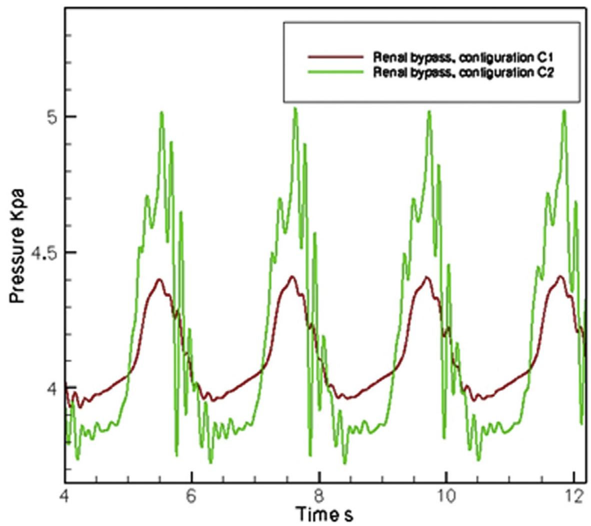

Fig. 5. Pressure wave measured in the renal bypass for the 2 different configurations. Configuration C1, red *line*; configuration C2, green *line*.

clarify whether there is a better technique: our results showed that the geometry of retrograde bypass may affect the pressure drop downstream of the bypass.

There are few papers published in the literature related to bypass complications after hybrid treatment. Chiesa et al. recently reported a 9.4% rate of visceral graft occlusion with a mean follow-up of 63.1 months. Hemodynamic repercussions were also observed at the level of the graft anastomosis to the superior mesenteric artery.[5]

Overall results regarding the visceral bypass showed good patency at mean follow-up. When graft occlusion occurs, it is probably due to many factors, many of those may be patient-related (technical execution of the anastomosis, different resistance in the vascular bed, different medical therapy). Alternatively, visceral and renal bypass can be performed with the VORTEC technique.[6] Recently, Winklehner et al.[7] reported long-term patency of visceral and renal bypass performed with the VORTEC technique.

In the course of our study, we observed a new aspect that was never investigated before in hybrid treatment: if the pressure actually drops downstream of the bypass, it has little effect on its patency, the geometry of the bypass causes a significant increase in the retrograde wave to the left ventricle, and this might have significant clinical repercussions.

The central aortic pressure wave comprises forward-traveling wave generated by left ventricular ejection and a later reflected wave from the periphery. As aortic and arterial stiffness increases, transmission velocity of both forward and reflected waves increases too, causing the reflected wave to reach the central aorta earlier, and augmenting pressure in late systole. Therefore, augmentation of the central aortic pressure wave is a manifestation of early wave reflection.[8]

Indeed, descending thoracic and abdominal aortic endografts increase aortic input and reflected waves. Lantelme et al.[9] showed that carotid—femoral pulse wave velocity increases after stent-graft deployment. Moreover, endovascular treatment leads to an increase in wave reflections compared with graft prosthesis. Dobson et al.[10] showed in an in vivo model that stent-graft deployment in the thoracic aorta increases wave velocity. According to our results, in hybrid treatment wave reflection increase may be even greater, as the wave reflections of the stent grafts are added to those of the graft prostheses used for debranching.

Our study showed an increase in wave reflections upstream of the treated ''aorta,'' demonstrating in vitro that hybrid treatment increases wave reflections.

Weber et al. showed that increased wave reflections predict severe cardiovascular events. Indeed, advancing age increases stiffness of the central elastic arteries, leading to an increase in the transmission velocity of both forward and backward pressure waves. This causes a reduction in diastolic pressure. In patients with diminished coronary reserve, the reduction in diastolic pressure can lead to ischemic events.[11,12] As shown by a previous experimental study, inserting a Dacron graft bypass increases the energy cost of the heart to maintain adequate flow in the coronary arteries. This too can worsen cardiac status in high-risk patients who should receive hybrid treatment.

CONCLUSION

Our preliminary results, obtained from an in vitro model of arterial circulation, suggest that both the debranching geometry and the material of the grafts and stent grafts significantly change the physiological arterial pressure. They show an increase in comparison with baseline physiological conditions upstream of debranching, possibly leading to an augmented pressure upstream of the stent grafts, due to retrograde pressure waves toward the heart, and to a decrease in pressure downstream in the visceral and renal arteries.

The hypothesis that hybrid treatment may have implications on hemodynamics is well founded.

Future studies should be aimed at optimizing these effects to improve postoperative short- and long-term results.

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