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SHORT REPORT

# Comparison of the Haemodynamic Performance of Various Treatment Options for Aorto-Iliac Occlusive Disease

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**Introduction:** Several surgical and endovascular techniques are used during the treatment of aorto-iliac occlusive disease. Aortobifemoral bypass (AoBFB) is the standard of care, but other options such as axillobifemoral (AxBFB) bypass, aorto-iliac kissing stents (KS), and covered endovascular reconstruction of aortic bifurcation (CERAB) are also available. This study aimed to perform a computational comparison of these four modalities to investigate their haemodynamic performance.
**Report:** Eight patient specific anatomies were analysed, with each of the abovementioned techniques used to treat two anatomies. The CT angiograms were segmented from the renal (or axillary) to common femoral arteries and the 3D geometries were exported. A commercial finite volume solver was implemented for numerical simulations. Outcomes that were assessed were pressure drop (ΔP) between the inlet and the outlet for every configuration and haemodynamic indices of Time Average Wall Shear Stress (TAWSS), Oscillatory Shear Index (OSI), and Relative Residence Time (RRT) as markers of a thrombogenic environment. The results indicate that maximum ΔP was observed at peak systole for all models, with values ranging between 12 mmHg and 21 mmHg for the AoBFB, 64 mmHg and 96 mmHg for the AxBFB, 31 mmHg and 46 mmHg for the KS, and 43 mmHg and 46 mmHg for the CERAB configuration. TAWSS, OSI, and RRT varied among different configurations, mostly presenting values well above thrombogenic thresholds. Regarding RRT, the percentage of total surface area presenting such values is 2.5%, 3.2%, 2%, and 4.3% for the AoBFB, AxBFB, KS, and CERAB configurations, respectively.
**Discussion:** Computational modelling indicates a favourable haemodynamic performance of AoBFB compared with the other configurations. This leads to a smaller pressure drop and sconsequently a higher pressure in the outlet of the conduit, which is the perfusion pressure of the limb. Notably, lower patency rates of the latter modalities cannot be explained based on haemodynamic indices.

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## INTRODUCTION

Aortobifemoral (AoBFB) bypass is the standard of care for patients with aorto-iliac occlusive disease but alternative treatment modalities are also available. Axillobifemoral bypass (AxBFB) is an alternative surgical option, mostly reserved for compromised patients, those with hostile abdomens, previous aortic graft infections, etc. Moreover, endovascular options such as kissing stenting (KS) and covered endovascular reconstruction of aortic bifurcation (CERAB) are also available for suitable patients. Previous literature suggests superior outcomes for AoBFB compared with the remaining modalities, although there are some reports that suggest similarly favourable outcomes.[1,2] A computational analysis comparing the abovementioned modalities has not been performed previously and would provide a theoretical basis to clinical data, assisting physicians during informed decision making and treatment.

## REPORT

A computational analysis was conducted of eight patient specific anatomies:

1. Two patients underwent AoBFB with an 18 x 9 mm bifurcated Dacron graft for acute aortic occlusion in one case and short distance intermittent claudication in the other.

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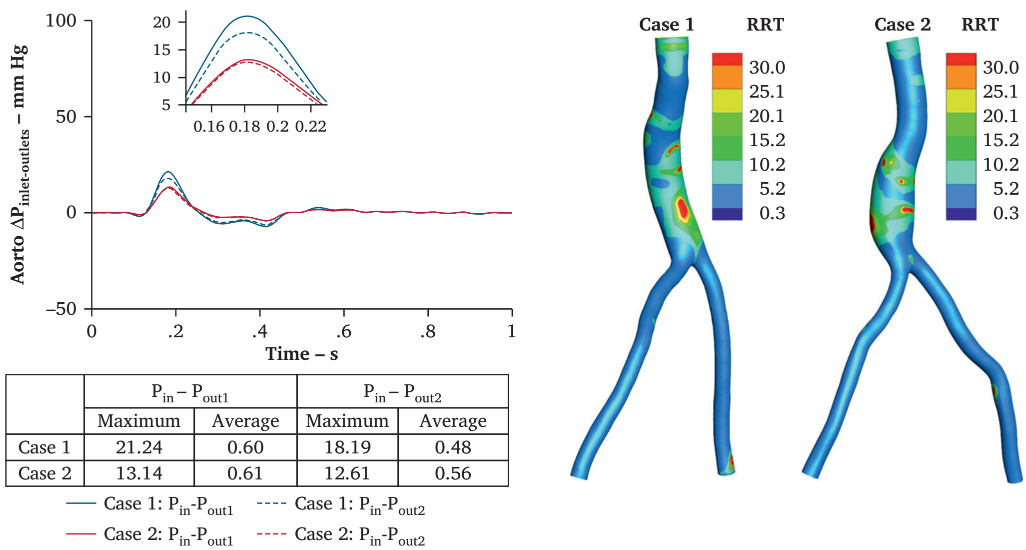
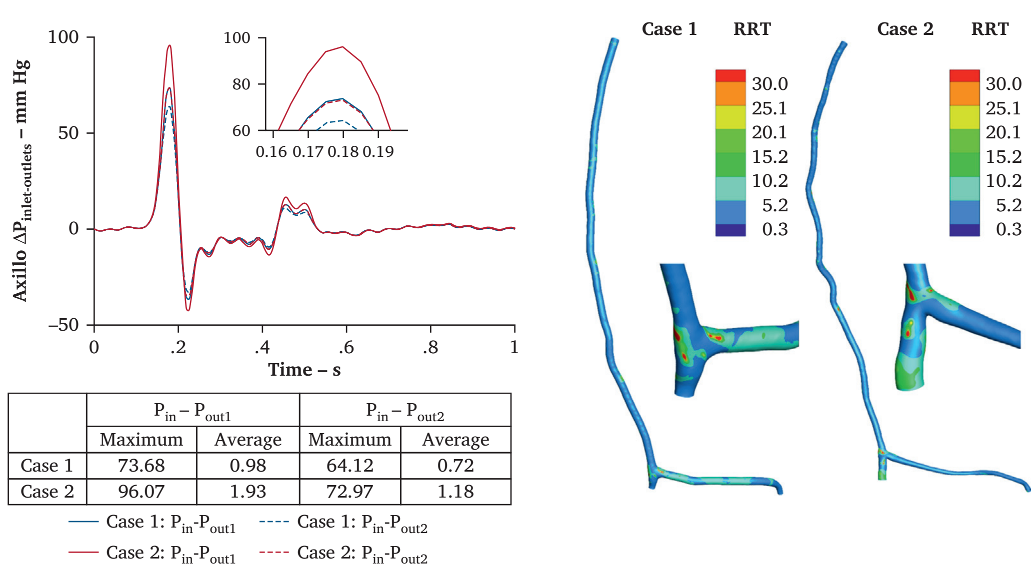



| | $P_{in} - P_{out1}$ | | $P_{in} - P_{out2}$ | |
|---|---|---|---|---|
| | Maximum | Average | Maximum | Average |
| Case 1 | 21.24 | 0.60 | 18.19 | 0.48 |
| Case 2 | 13.14 | 0.61 | 12.61 | 0.56 |

**Figure 1.** For the aortobifemoral bypass (AoBFB) configuration, a graphical representation of pressure drop (ΔP) over time is provided for a cardiac cycle of one second. ΔP is the difference between pressure at the inlet and pressure calculated at the outlet. Two values of ΔP are calculated for every case, one for each of the two outlets (common femoral arteries bilaterally) and it can be seen that differences between outlets are not remarkable. A colour map of Relative Residence Time (RRT) is also provided and displayed in the three dimensionally reconstructed patient specific geometries. A table with numerical values of maximum and average ΔP for the two cases and both outlets is also embedded.

2. Two patients received an AxBFB with an externally supported 8 mm ePTFE graft for acute aortic occlusion and chronic limb threatening ischaemia (CLTI).
3. Two patients were treated with aorto-iliac balloon expandable KS 8 mm (Advanta V12-Atrium, Hudson, NH, USA) for CLTI.
4. Two patients underwent CERAB (proximally 12 mm Advanta V12 and distally 8 mm Advanta V12) for CLTI.

CT angiography images were obtained with similar technical parameters for all patients: 0.625 mm × 64 mm collimation; 0.4 s gantry rotation time; pitch of 1.375; reconstruction slice thickness 1.25 mm. Three dimensional models were reconstructed from CT angiography images with manual segmentation from the renals (AoBFB, KS, CERAB) or the axillary artery (AxBFB) to the common femoral arteries (3D Slicer, Open source software). Blood was modelled as homogeneous, incompressible, and non-Newtonian fluid. A commercial finite volume solver was implemented (Fluent 17.2, ANSYS Inc.) for numerical simulations with a convergence criterion $10^{-4}$. The time step was kept constant and equal to 0.005 seconds for a cardiac cycle of 1 second. A rigid wall with no slip boundary condition was assumed. A transient velocity that followed




| | $P_{in} - P_{out1}$ | | $P_{in} - P_{out2}$ | |
|---|---|---|---|---|
| | Maximum | Average | Maximum | Average |
| Case 1 | 73.68 | 0.98 | 64.12 | 0.72 |
| Case 2 | 96.07 | 1.93 | 72.97 | 1.18 |

**Figure 2.** Similar information to that in Fig. 1 is presented for the axillobifemoral (AxBFB) configuration.

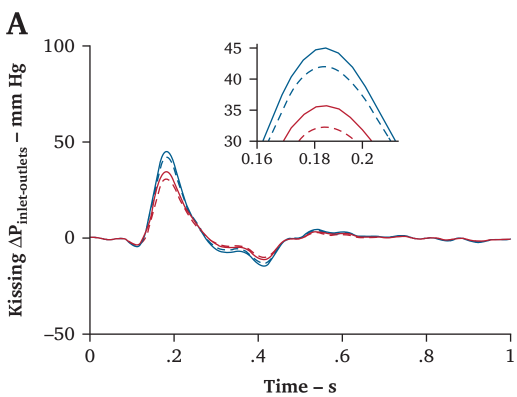
Olufsen et al. was prescribed at the inlet of AoBFB, KS, and CERAB geometries, while the velocity profile reported by Gupta et al. was prescribed at the inlet of the AxBFB model.[3,4] A standard outflow condition was assumed.

The following outcomes were assessed:

1. The pressure drop (ΔP) between the inlet and the outlet for every configuration, which was considered an index of its haemodynamic performance, i.e., the higher the ΔP, the higher the resistance leading to a reduced pressure at the outlet for an adequate flow to be maintained. Pressure at the outlet (Pout) of each case represents the perfusion pressure of the limb. Both maximum ΔP and average (throughout the cardiac cycle) ΔP were calculated.
2. Haemodynamic indices of Time Average Wall Shear Stress (TAWSS), Oscillatory Shear Index (OSI), and Relative Residence Time (RRT) as markers of a thrombogenic environment to explain differences in patency rates.

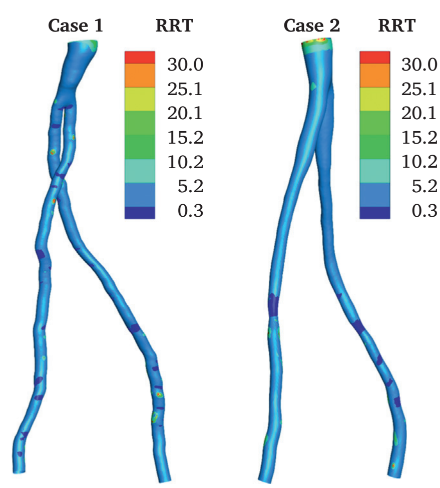
Maximum ΔP was observed at peak systole for all models, with a mean value of 16.2 mmHg, 76.7 mmHg, 38.6 mmHg, and 44.3 mmHg for the AoBFB, AxBFB, KS, and CERAB, respectively, as seen in Figs. 1–3. Taking into account average ΔP, differences were not so pronounced, but still the AoBFB presented the lowest value (0.56 mmHg), compared with the AxBFB (1.2 mmHg), the KS (2.4 mmHg), and the CERAB (5.2 mmHg) configurations.

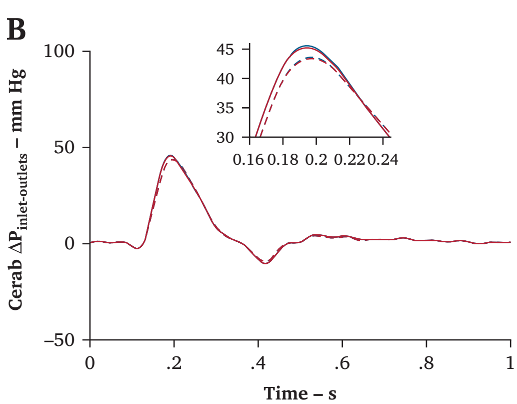
TAWSS, OSI, and RRT varied among different configurations. Taking into account RRT, which is an index that is




| | $P_{in} - P_{out1}$ | | $P_{in} - P_{out2}$ | |
|---|---|---|---|---|
| | Maximum | Average | Maximum | Average |
| Case 1 | 45.68 | 2.67 | 42.30 | 2.62 |
| Case 2 | 35.33 | 2.35 | 31.29 | 2.06 |

Case 1: $P_{in}$-$P_{out1}$ Case 1: $P_{in}$-$P_{out2}$
Case 2: $P_{in}$-$P_{out1}$ Case 2: $P_{in}$-$P_{out2}$




| | $P_{in} - P_{out1}$ | | $P_{in} - P_{out2}$ | |
|---|---|---|---|---|
| | Maximum | Average | Maximum | Average |
| Case 1 | 45.44 | 5.33 | 43.46 | 5.20 |
| Case 2 | 45.25 | 5.31 | 43.28 | 5.18 |

Case 1: $P_{in}$-$P_{out1}$ Case 1: $P_{in}$-$P_{out2}$
Case 2: $P_{in}$-$P_{out1}$ Case 2: $P_{in}$-$P_{out2}$

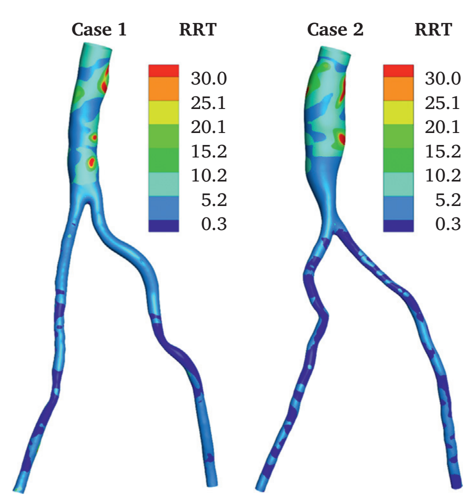



**Figure 3.** Similar information to that in Fig. 1 is presented for the endovascular techniques (A) aorto-iliac kissing stents (KS) and (B) covered endovascular reconstruction of aortic bifurcation (CERAB).

dependent on both TAWSS and OSI, reflects the residence time of blood near the wall and has previously been associated with thrombus formation, the percentage of total surface area presenting thrombogenic values varied between 1% and 5% among the different configurations (AoBFB 2.5%, AxBFB 3.2%, KS 2.3%, CERAB 4.4%).[5]

## DISCUSSION

The main finding of the present analysis is the favourable haemodynamic performance of AoBFB compared with the rest of the possible configurations used for aorto-iliac recanalisation, as indicated by the lower $\Delta P$ that was calculated. Although data have been reported to indicate a favourable clinical outcome after AoBFB compared with AxBFB regarding restoration of distal pulses and normalisation of Ankle Brachial Index (ABI), these are scarce and are certainly dependent on the outflow conditions of patient.[6] Notably, no comparative data could be retrieved to evaluate the clinical outcome of the remaining configurations, although notable improvements in arterial perfusion of the lower limbs have been reported with all the available modalities.[7–9]

Haemodynamic variables that were recorded do not provide a convincing explanation as to why AxBFB and endovascular methods usually enjoy lower primary patency rates than AoBFB. The percentage of total surface area under thrombogenic haemodynamic conditions ranged from 1% to 5% for all configurations. For the current analysis a RRT value $>10$ Pa$^{-1}$ was used as a threshold to define a thrombogenic haemodynamic environment, as previously reported in the literature.[5] Therefore, other factors such as neointimal hyperplasia, difference in outflow disease, residual stenosis after endovascular treatment, and total atherosclerotic burden may play a more prominent role in patency rates. Nevertheless, according to previous literature, although primary patency is higher after AoBFB, secondary patency is similarly favourable with standard endovascular treatment and CERAB.[2]

A possible limitation of the current analysis is that the haemodynamic conditions taken into account to determine a thrombogenic environment may be suboptimal due to the lack of an adequate definition in the existing literature. Nevertheless, the thresholds that have been set in the present study represent the most commonly used values that are considered both atherogenic (in the presence of a normal endothelial layer in native vessel) and thrombogenic (i.e., inside branches of endografts). Therefore, despite the variability of thresholds reported in previous studies, the values that have been selected represent the closest approximation of most commonly reported values.[10]

In conclusion, computational modelling indicates a favourable haemodynamic performance of AoBFB compared with AxBFB and endovascular therapies during aorto-iliac recanalisation. However, the difference in patency rates cannot be explained based on haemodynamic indices and may rely on alternative factors.

## CONFLICT OF INTEREST

None.

## FUNDING

None.

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