A computational analysis of branched endograft designs for zone 0 endovascular aortic arch repair

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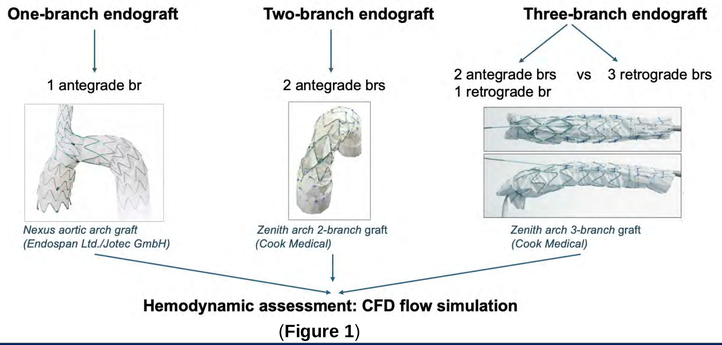
OBJECTIVES

- To evaluate the hemodynamic response induced by implantation of zone 0 branched endografts

METHODS

- This retrospective multicenter study included 29 patients who underwent zone 0 endovascular repair using 1-, 2-, 3-branch endografts (n=7, n=11, n=11, respectively), using the Nexus system (Endospan Ltd.) and Zenith Arch Branch Device (Cook Medical). All 2-branch endografts were designed with two antegrade branches. Of eleven 3-branch endografts, eight endografts were designed with two antegrade and one retrograde branches, and the other three with three retrograde branches. Any extra-anatomical bypasses (IA-LCCA-LSA bypass, LCCA-LSA bypass) were included in the analysis. Pre- and Post-implantation aortic models were reconstructed from patients' computed tomography (CT) scans and 58 computational fluid dynamics (CFD) simulations were performed (Figure 1).



(**Figure 1**)

RESULTS

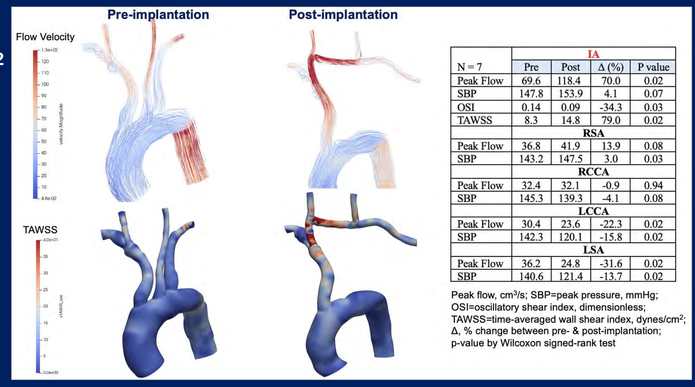
Single branch endografts (Figure 2)

- The single branch design resulted in increased flow into the IA, which is now the only supra-aortic branch directly perfused through the arch, and it had to carry additional flow to supply the LCCA and LSA. This affected perfusion of RCCA, LCCA, LSA - lowering flow rate.
- TAWSS was higher due to the higher flow in the IA.
- The branching zone where the IA splits into the RCCA creates a region with higher WSS due to the change in blood flow separation/redirection at the bifurcation point. This also occurred in the branching zone of the RCCA-LCCA bypass, showing disturbed flow patterns leading to localized areas of elevated TAWSS.

Double branch endografts (Figure 3)

- As seen in post-implantation model, excluding the aneurysm via a branched endograft restored a more desirable flow pattern in the arch.
- Flow velocities increased in the IA & LCCA due to the presence of the inner branches, as insertion of the inner branch reduced the lumen area resulting in acceleration of blood flow.
- The high velocity flow through the inner tunnels impacted on the branch vessel walls when changing its direction, resulting in very high WSS in the IA & LCCA.
- High TAWSS was also found at the anastomosis between the bypass and the LCCA.

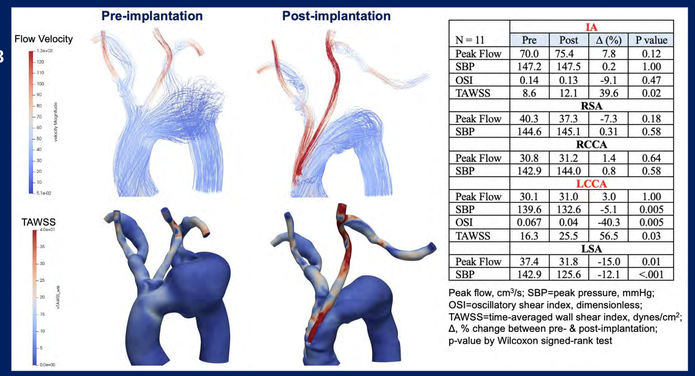
Figure 2



N = 7	Pre	Post	Δ (%)	P value
	IA			
Peak Flow	69.6	118.4	70.0	0.02
SBP	147.8	153.9	4.1	0.07
OSI	0.14	0.09	-34.3	0.03
TAWSS	8.3	14.8	79.0	0.02
	RSA			
Peak Flow	36.8	41.9	13.9	0.08
SBP	143.2	147.5	3.0	0.03
	RCCA			
Peak Flow	32.4	32.1	-0.9	0.94
SBP	145.3	139.3	-4.1	0.08
	LCCA			
Peak Flow	30.4	23.6	-22.3	0.02
SBP	142.3	120.1	-15.8	0.02
	LSA			
Peak Flow	36.2	24.8	-31.6	0.02
SBP	140.6	121.4	-13.7	0.02

Peak flow, cm^3/s; SBP=peak pressure, mmHg; OSI=oscillatory shear index, dimensionless; TAWSS=time-averaged wall shear index, $dynes/cm^2$; Δ, % change between pre- & post-implantation; p-value by Wilcoxon signed-rank test

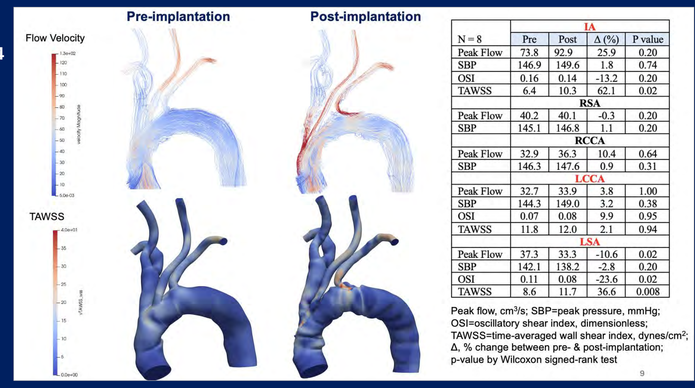
Figure 3



N = 11	Pre	Post	Δ (%)	P value
	IA			
Peak Flow	70.0	75.4	7.8	0.12
SBP	147.2	147.5	0.2	1.00
OSI	0.14	0.13	-9.1	0.47
TAWSS	8.6	12.1	39.6	0.02
	RSA			
Peak Flow	40.3	37.3	-7.3	0.18
SBP	144.6	145.1	0.31	0.58
	RCCA			
Peak Flow	30.8	31.2	1.4	0.64
SBP	142.9	144.0	0.8	0.58
	LCCA			
Peak Flow	30.1	31.0	3.0	1.00
SBP	139.6	132.6	-5.1	0.005
OSI	0.067	0.04	-40.3	0.005
TAWSS	16.3	25.5	56.5	0.03
	LSA			
Peak Flow	37.4	31.8	-15.0	0.01
SBP	142.9	125.6	-12.1	<.001

Peak flow, cm^3/s; SBP=peak pressure, mmHg; OSI=oscillatory shear index, dimensionless; TAWSS=time-averaged wall shear index, $dynes/cm^2$; Δ, % change between pre- & post-implantation; p-value by Wilcoxon signed-rank test

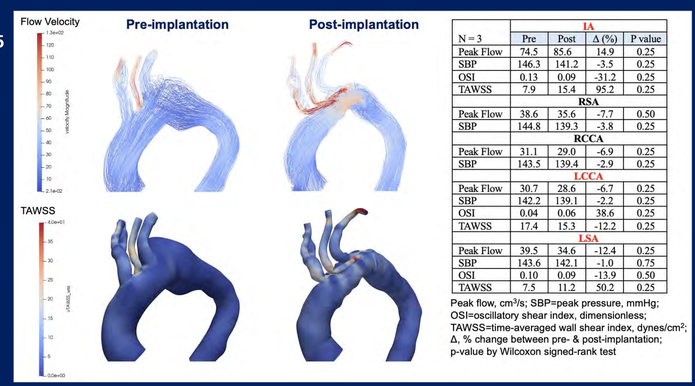
Figure 4



N = 8	Pre	Post	Δ (%)	P value
	IA			
Peak Flow	73.8	92.9	25.9	0.20
SBP	146.9	149.6	1.8	0.74
OSI	0.16	0.14	-13.2	0.20
TAWSS	6.4	10.3	62.1	0.02
	RSA			
Peak Flow	40.2	40.1	-0.3	0.20
SBP	145.1	146.8	1.1	0.20
	RCCA			
Peak Flow	32.9	36.3	10.4	0.64
SBP	146.3	147.6	0.9	0.31
	LCCA			
Peak Flow	32.7	33.9	3.8	1.00
SBP	144.3	149.0	3.2	0.38
OSI	0.07	0.08	9.9	0.95
TAWSS	11.8	12.0	2.1	0.94
	LSA			
Peak Flow	37.3	33.3	-10.6	0.02
SBP	142.1	138.2	-2.8	0.20
OSI	0.11	0.08	-23.6	0.02
TAWSS	8.6	11.7	36.6	0.008

Peak flow, cm^3/s; SBP=peak pressure, mmHg; OSI=oscillatory shear index, dimensionless; TAWSS=time-averaged wall shear index, $dynes/cm^2$; Δ, % change between pre- & post-implantation; p-value by Wilcoxon signed-rank test

Figure 5



N = 3	Pre	Post	Δ (%)	P value
	IA			
Peak Flow	74.5	85.6	14.9	0.25
SBP	146.3	141.2	-3.5	0.25
OSI	0.13	0.09	-31.2	0.25
TAWSS	7.9	15.4	95.2	0.25
	RSA			
Peak Flow	38.6	35.6	-7.7	0.50
SBP	144.8	139.3	-3.8	0.25
	RCCA			
Peak Flow	31.1	29.0	-6.9	0.25
SBP	143.5	139.4	-2.9	0.25
	LCCA			
Peak Flow	30.7	28.6	-6.7	0.25
SBP	142.2	139.1	-2.2	0.25
OSI	0.04	0.06	38.6	0.25
TAWSS	17.4	15.3	-12.2	0.25
	LSA			
Peak Flow	39.5	34.6	-12.4	0.25
SBP	143.6	142.1	-1.0	0.75
OSI	0.10	0.09	-13.9	0.50
TAWSS	7.5	11.2	50.2	0.25

Peak flow, cm^3/s; SBP=peak pressure, mmHg; OSI=oscillatory shear index, dimensionless; TAWSS=time-averaged wall shear index, $dynes/cm^2$; Δ, % change between pre- & post-implantation; p-value by Wilcoxon signed-rank test

RESULTS (con't)

Triple branch: 2 antegrade+1 retrograde (Figure 4)

- When the internal side branch is antegrade, as with IA and LCCA, the flow rate is larger than the original flow.
- Compared to an antegrade orientation, with a retrograde orientation of the LSA, the blood flow must change direction to pass through the branch stent graft. Consequently, it lowers the flow velocity and pressure.
- TAWSS in the IA was higher than the pre-implantation due to the higher flow rate.
- High WSS regions occur at the origin of all side branches.

Triple branch: 3 retrograde (Figure 5)

- With retrograde branch orientation, changes in peak flow rates were mild.
- The associated pressure changes with branch stent graft orientation are also relatively unaffected.
- Regions of high TAWSS occurred at the origins of all side branches due to abrupt changes in flow direction as well as cross-sectional areas for the blood flow.
- The high velocity flow through the inner branch tunnels created complex flow pattern, resulting in high WSS.

2 antegrade+1 retrograde vs 3 retrograde configurations (Figure 6)

- A retrograde inner branch had a decrease in flow rate.
- In contrast, the more proximal artery, IA had an increase in flow rate regardless of the orientation.
- LCCA, located between IA and LSA, was less affected.

CONCLUSION

- Changing the number of branches influences local hemodynamic patterns inside the arch vessels.
- Hemodynamic changes decrease as the number of branches increase (Figure 7).
- Further innovation to improve access to 3-branch designs will mitigate hemodynamic changes in the arch vessels.

Figure 6

Figure 7