VASCUPEDIA

Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

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VASCUPEDIA

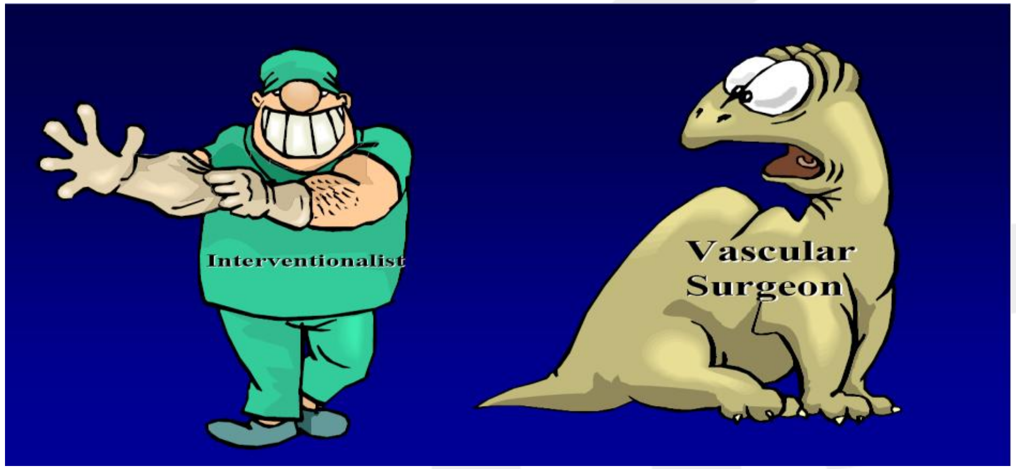
Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

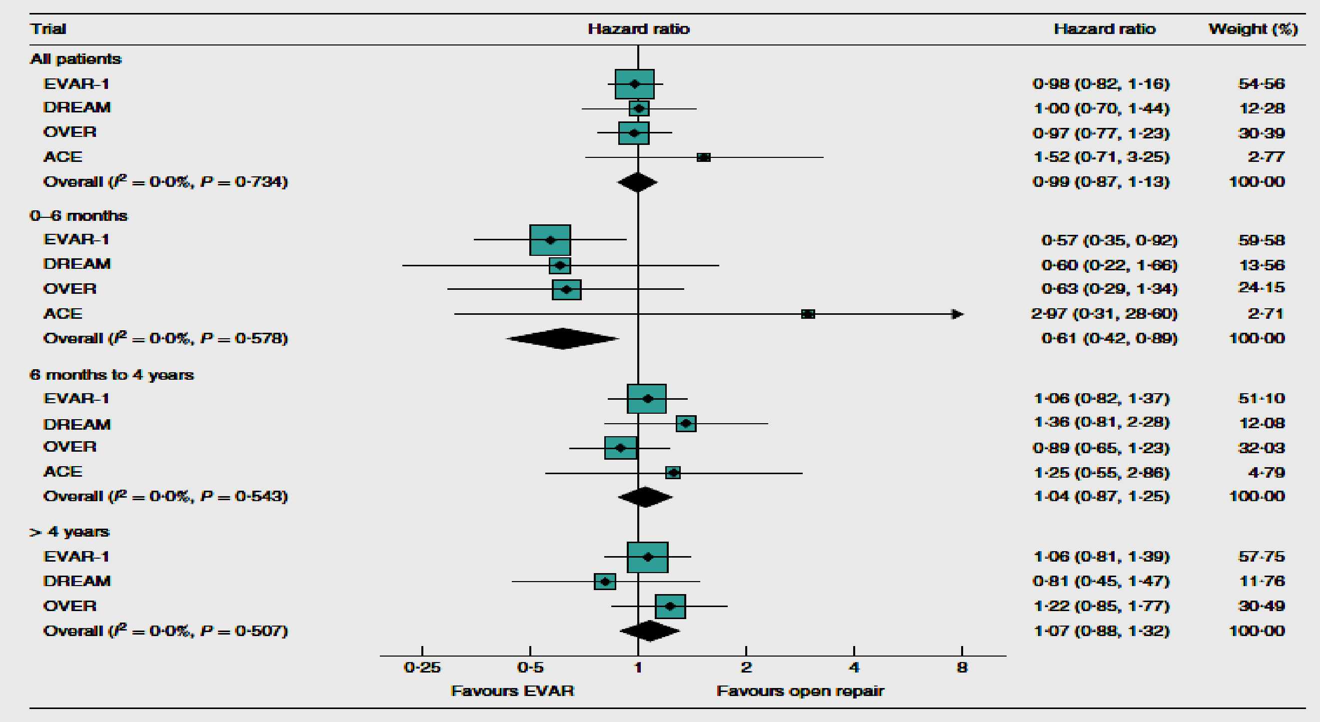
- Disclosures: none
- Conflict of interest: none

Endovascular- vs. open repair: is the battle over?

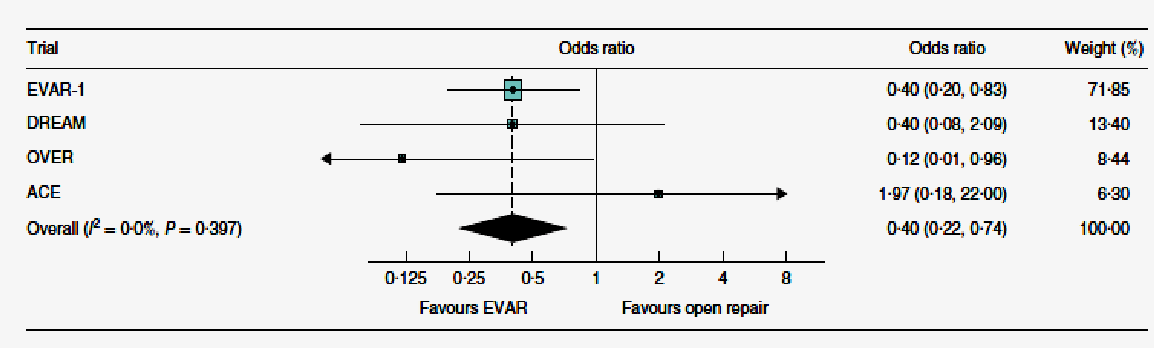
Meta-analysis of individual-patient data from EVAR-1, DREAM, OVER and ACE trials comparing outcomes of endovascular or open repair for abdominal aortic aneurysm over 5 years

J. T. Powell[1], M. J. Sweeting[2], P. Ulug[1], J. D. Blankensteijn[3], F. A. Lederle[4], J.-P. Becquemin[5] and R. M. Greenhalgh[1], on behalf of the EVAR-1, DREAM, OVER and ACE Trialists



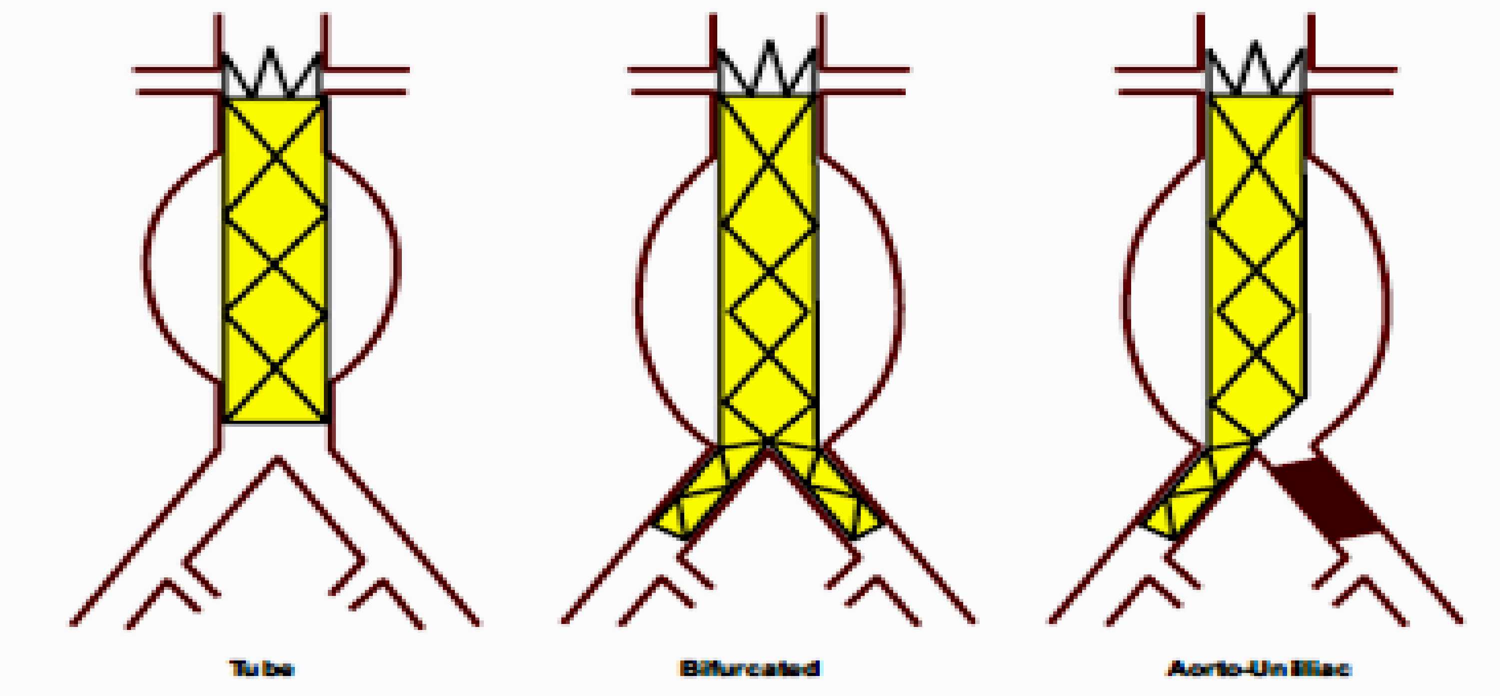


Trial	Hazard ratio	Weight (%)
All patients		
EVAR-1	0·98 (0·82, 1·16)	54·56
DREAM	1·00 (0·70, 1·44)	12·28
OVER	0·97 (0·77, 1·23)	30·39
ACE	1·52 (0·71, 3·25)	2·77
Overall ($I^2 = 0·0\%$, $P = 0·734$)	0·99 (0·87, 1·13)	100·00
0–6 months		
EVAR-1	0·57 (0·35, 0·92)	59·58
DREAM	0·60 (0·22, 1·66)	13·56
OVER	0·63 (0·29, 1·34)	24·15
ACE	2·97 (0·31, 28·60)	2·71
Overall ($I^2 = 0·0\%$, $P = 0·578$)	0·61 (0·42, 0·89)	100·00
6 months to 4 years		
EVAR-1	1·06 (0·82, 1·37)	51·10
DREAM	1·36 (0·81, 2·28)	12·08
OVER	0·89 (0·65, 1·23)	32·03
ACE	1·25 (0·55, 2·86)	4·79
Overall ($I^2 = 0·0\%$, $P = 0·543$)	1·04 (0·87, 1·25)	100·00
> 4 years		
EVAR-1	1·06 (0·81, 1·39)	57·75
DREAM	0·81 (0·45, 1·47)	11·76
OVER	1·22 (0·85, 1·77)	30·49
Overall ($I^2 = 0·0\%$, $P = 0·507$)	1·07 (0·88, 1·32)	100·00



Trial	Odds ratio	Weight (%)
EVAR-1	0·40 (0·20, 0·83)	71·85
DREAM	0·40 (0·08, 2·09)	13·40
OVER	0·12 (0·01, 0·96)	8·44
ACE	1·97 (0·18, 22·00)	6·30
Overall ($I^2 = 0·0\%$, $P = 0·397$)	0·40 (0·22, 0·74)	100·00

Common endograft designs when treating AAA




NEW APPROACHES TO
AORTIC DISEASES
from Valve to Abdominal Bifurcation

Editors
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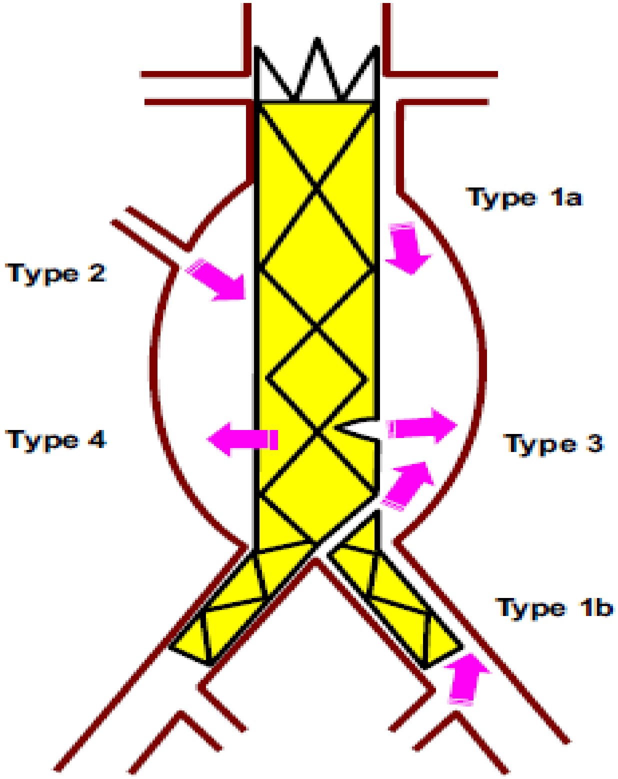
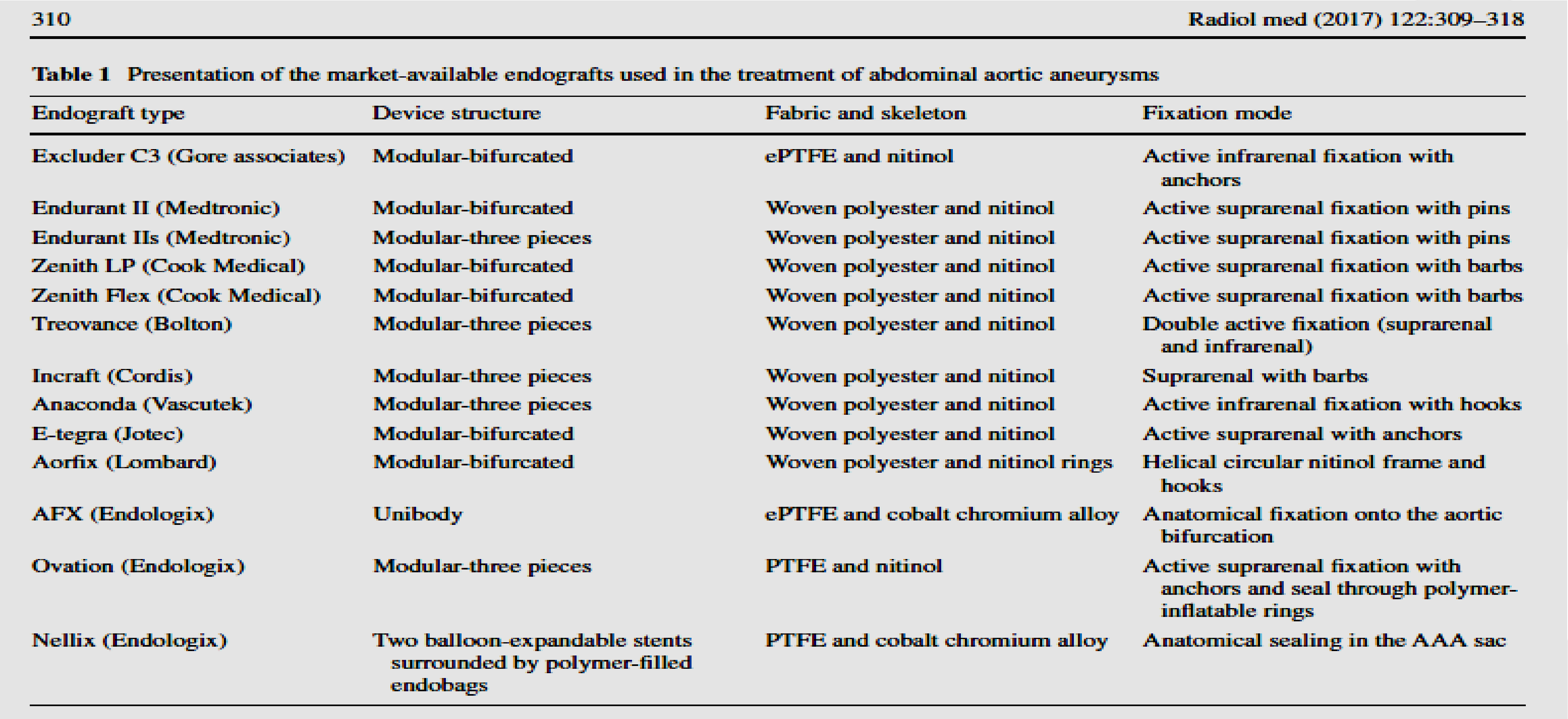


FIGURE 38.2 Types of endoleaks.

TYPES OF ENDOLEAKS

Common endograft designs when treating AAA

Most commercially available endografts carry a Nitinol skeleton on Dacron or PTFE fabric with various fixation modes



310 Radiol med (2017) 122:309–318

Table 1 Presentation of the market-available endografts used in the treatment of abdominal aortic aneurysms

Endograft type	Device structure	Fabric and skeleton	Fixation mode
Excluder C3 (Gore associates)	Modular-bifurcated	ePTFE and nitinol	Active infrarenal fixation with anchors
Endurant II (Medtronic)	Modular-bifurcated	Woven polyester and nitinol	Active suprarenal fixation with pins
Endurant IIs (Medtronic)	Modular-three pieces	Woven polyester and nitinol	Active suprarenal fixation with pins
Zenith LP (Cook Medical)	Modular-bifurcated	Woven polyester and nitinol	Active suprarenal fixation with barbs
Zenith Flex (Cook Medical)	Modular-bifurcated	Woven polyester and nitinol	Active suprarenal fixation with barbs
Treovance (Bolton)	Modular-three pieces	Woven polyester and nitinol	Double active fixation (suprarenal and infrarenal)
Incraft (Cordis)	Modular-three pieces	Woven polyester and nitinol	Suprarenal with barbs
Anaconda (Vascutek)	Modular-three pieces	Woven polyester and nitinol	Active infrarenal fixation with hooks
E-tegra (Jotec)	Modular-bifurcated	Woven polyester and nitinol	Active suprarenal with anchors
Aorfix (Lombard)	Modular-bifurcated	Woven polyester and nitinol rings	Helical circular nitinol frame and hooks
AFX (Endologix)	Unibody	ePTFE and cobalt chromium alloy	Anatomical fixation onto the aortic bifurcation
Ovation (Endologix)	Modular-three pieces	PTFE and nitinol	Active suprarenal fixation with anchors and seal through polymer-inflatable rings
Nellix (Endologix)	Two balloon-expandable stents surrounded by polymer-filled endobags	PTFE and cobalt chromium alloy	Anatomical sealing in the AAA sac

Schoretsanitis et al, Radiol Med 2017; 122:306-318

Common endograft designs when treating AAA

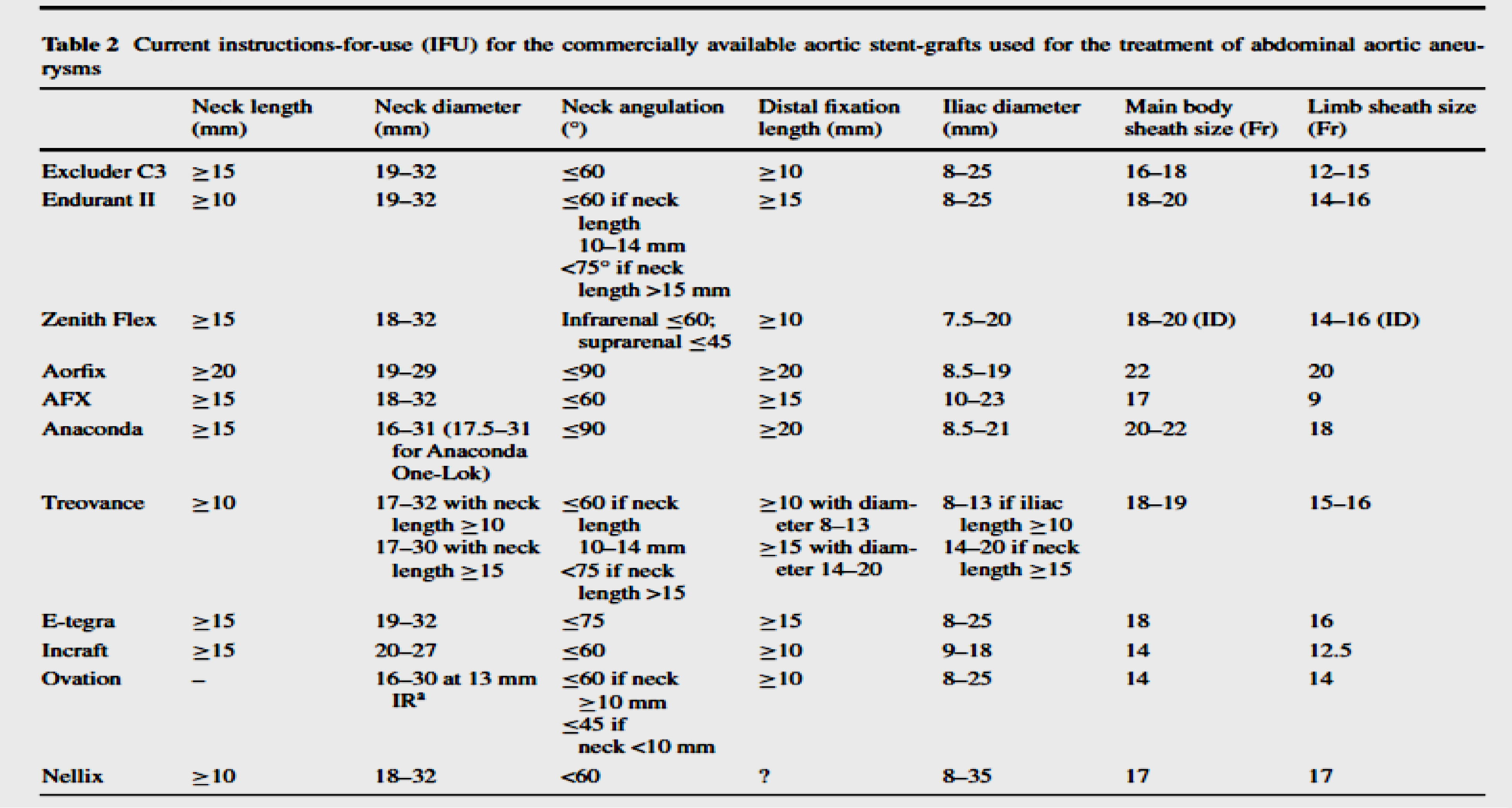
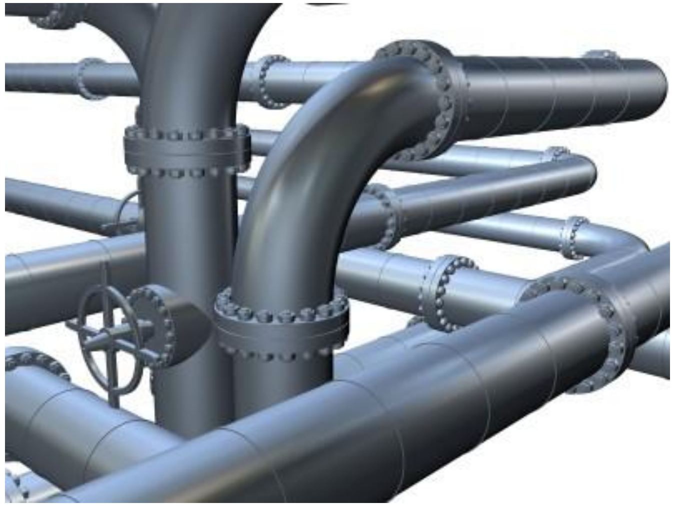


Table 2 Current instructions-for-use (IFU) for the commercially available aortic stent-grafts used for the treatment of abdominal aortic aneurysms

	Neck length (mm)	Neck diameter (mm)	Neck angulation (°)	Distal fixation length (mm)	Iliac diameter (mm)	Main body sheath size (Fr)	Limb sheath size (Fr)
Excluder C3	≥15	19–32	≤60	≥10	8–25	16–18	12–15
Endurant II	≥10	19–32	≤60 if neck length 10–14 mm <75° if neck length >15 mm	≥15	8–25	18–20	14–16
Zenith Flex	≥15	18–32	Infrarenal ≤60; suprarenal ≤45	≥10	7.5–20	18–20 (ID)	14–16 (ID)
Aorfix	≥20	19–29	≤90	≥20	8.5–19	22	20
AFX	≥15	18–32	≤60	≥15	10–23	17	9
Anaconda	≥15	16–31 (17.5–31 for Anaconda One-Lok)	≤90	≥20	8.5–21	20–22	18
Treovance	≥10	17–32 with neck length ≥10 17–30 with neck length ≥15	≤60 if neck length 10–14 mm <75 if neck length >15	≥10 with diameter 8–13 ≥15 with diameter 14–20	8–13 if iliac length ≥10 14–20 if neck length ≥15	18–19	15–16
E-tegra	≥15	19–32	≤75	≥15	8–25	18	16
Incraft	≥15	20–27	≤60	≥10	9–18	14	12.5
Ovation	–	16–30 at 13 mm IR[a]	≤60 if neck ≥10 mm ≤45 if neck <10 mm	≥10	8–25	14	14
Nellix	≥10	18–32	<60	?	8–35	17	17

Schoretsanitis et al, Radiol Med 2017; 122:306-318

EVAR: simple hydraulics? Not exactly!!

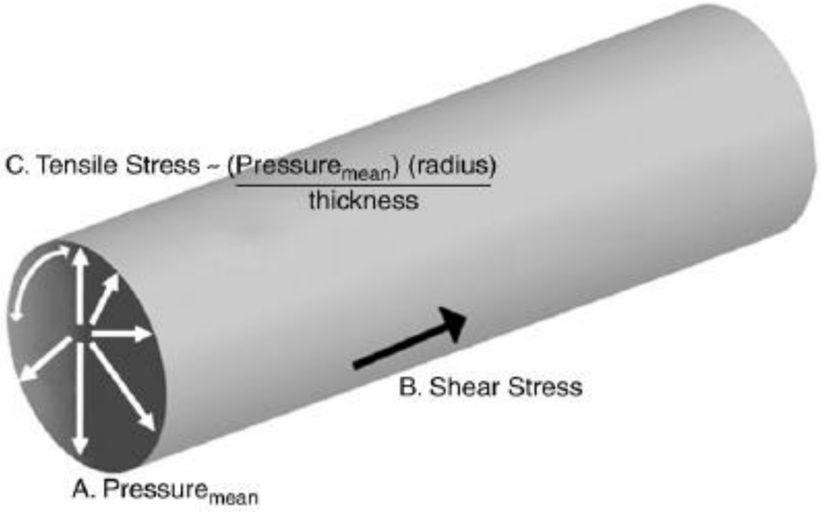




The short-, med- and long tern performance of endografts depends on the mechanical properties of endografts and aorta (aneurysm)

Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

Aim of this presentation is to describe and comprehend the hemodynamic phenomena taking place after Endograft implantation and get familiar with basic hemodynamic and mechanical terms

Introduction to basic principles



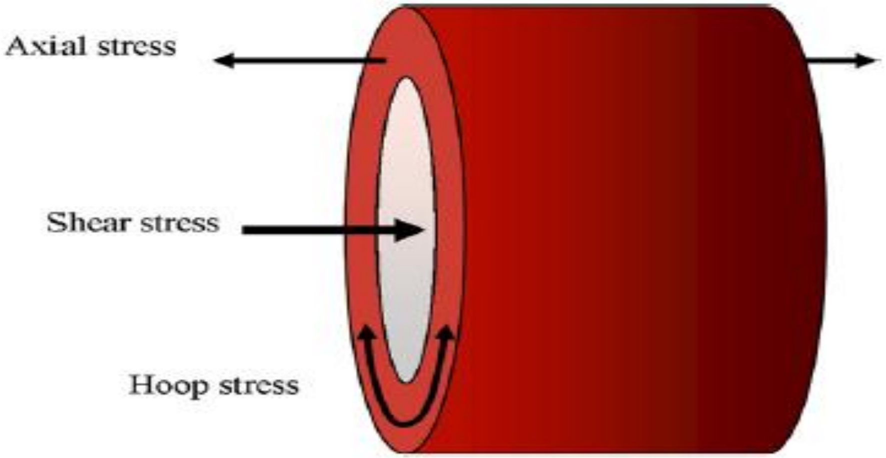
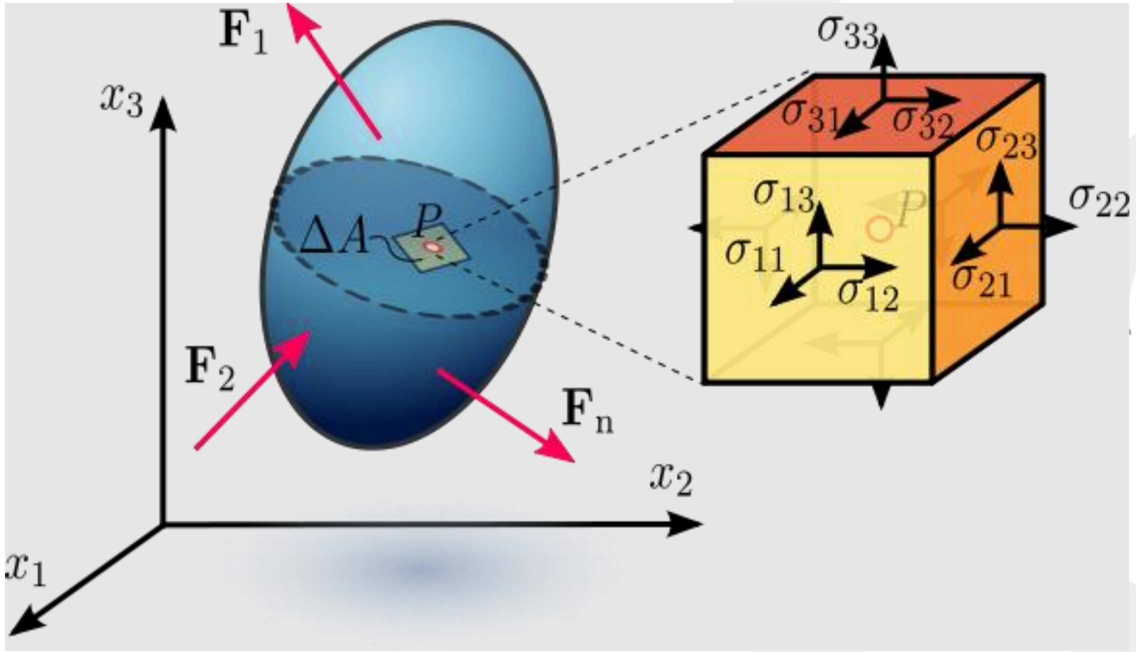


Fig 1. Forces acting on the aortic wall.

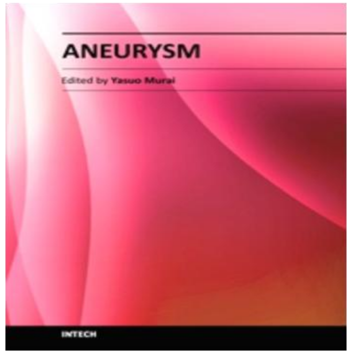


Dua & Dalman, Vascul Pharmacol. 2010; 53:11-21

Introduction to basic principles

The pressure forces act perpendicularly on the wall surface.

Shear forces are tangential to the surface as a result of flow and are responsible for intimal hyperplasia, stenosis and thrombus formation


ANEURYSM

Edited by Yasuo Murai

INTECH

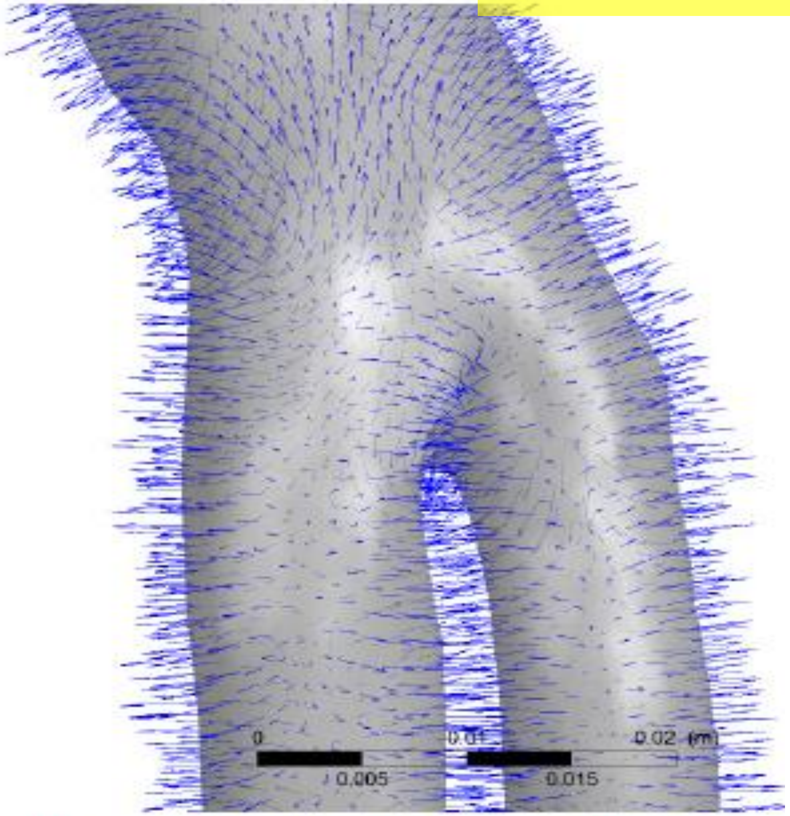


Figure 18. The pressure forces on the endograft bifurcation area (peak sys

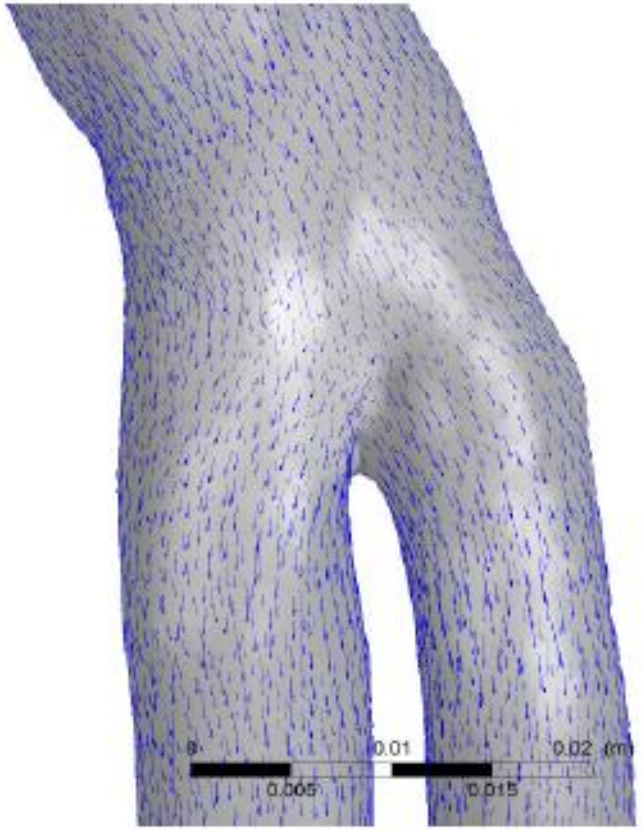
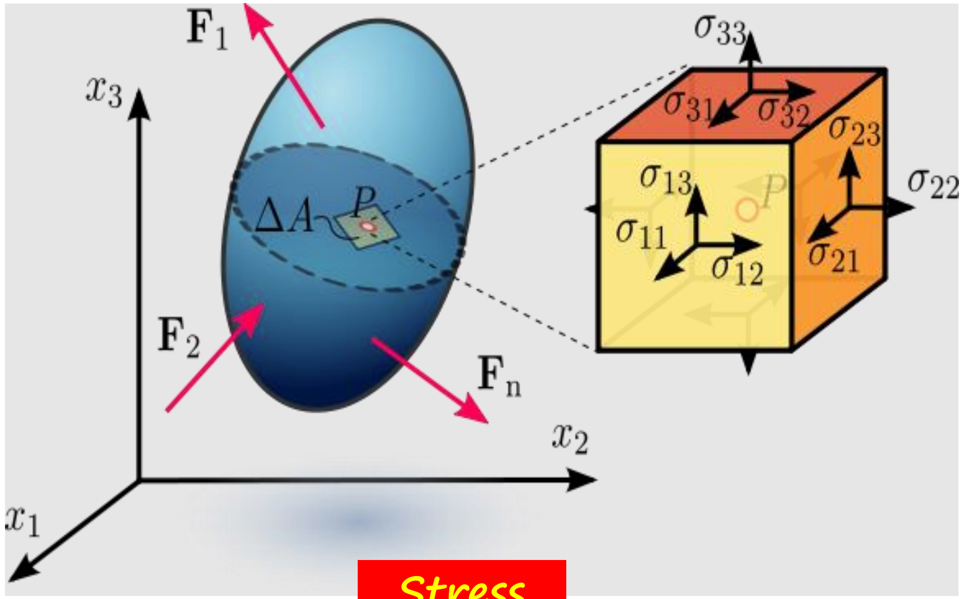


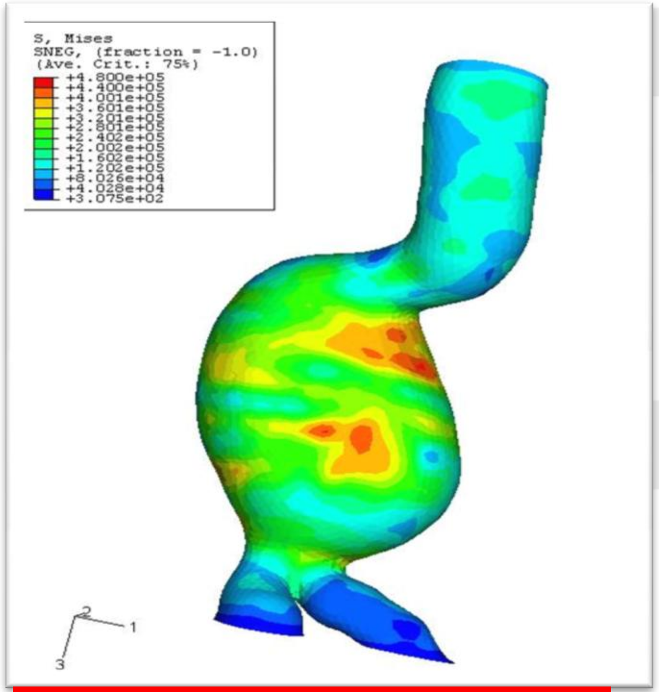
Figure 19. The tangential forces on the endograft bifurcation area (peak systolic phase).

Introduction to basic principles

- ✓ The term "stress" refers to the energy load on a given structure
- ✓ Under any pressure, produces strain and is counteracted by the mechanical strength of the structure



Georgakarakos et al, Int Angiol, 2009; 325-33



Peak wall stress (PWS)

$$\sigma_{VM} = \sqrt{{}^{1}/{}_{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_2)^2]}$$

von Mises stress

Depends on:

1. Geometry
2. Mechanical properties
3. Systolic pressure
4. Wall thickness

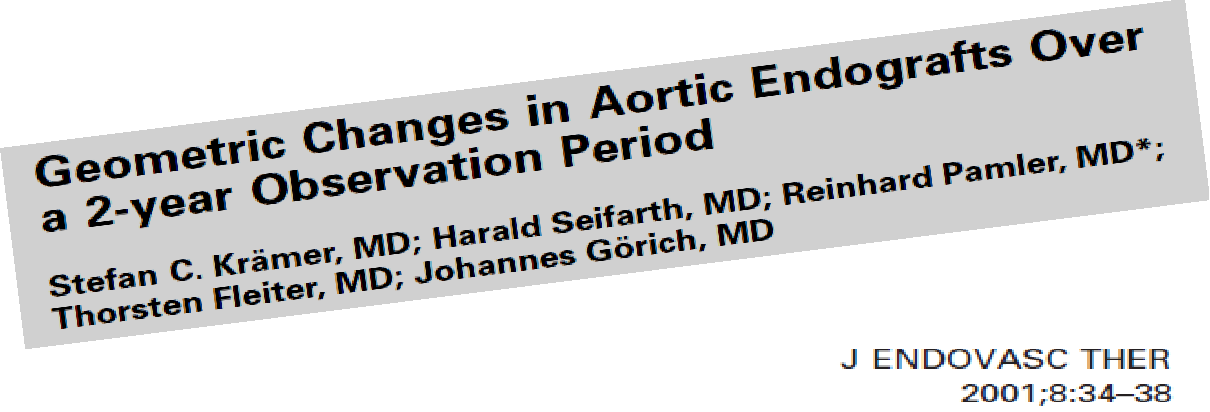
Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

PERFORMANCE OF ENDOGRAFS

REMODELLING

- ✓MECHANICAL PROPERTIES
- ✓FORCES
- ✓STRESSES
- ✓GEOMETRY

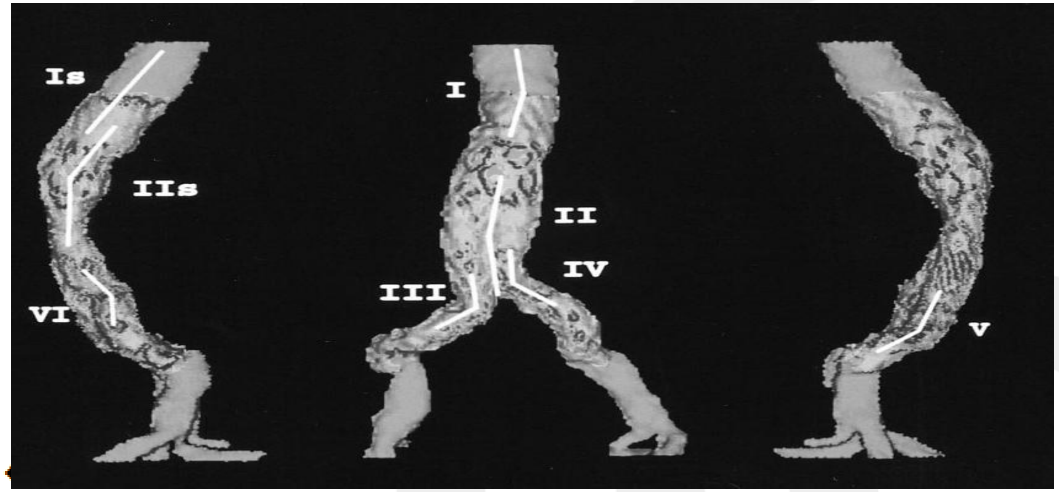
Remodelling: decrease of angulation of infarenal neck AND iliacs



Geometric Changes in Aortic Endografts Over a 2-year Observation Period

Stefan C. Krämer, MD; Harald Seifarth, MD; Reinhard Pamler, MD*; Thorsten Fleiter, MD; Johannes Görich, MD

J ENDOVASC THER
2001;8:34–38



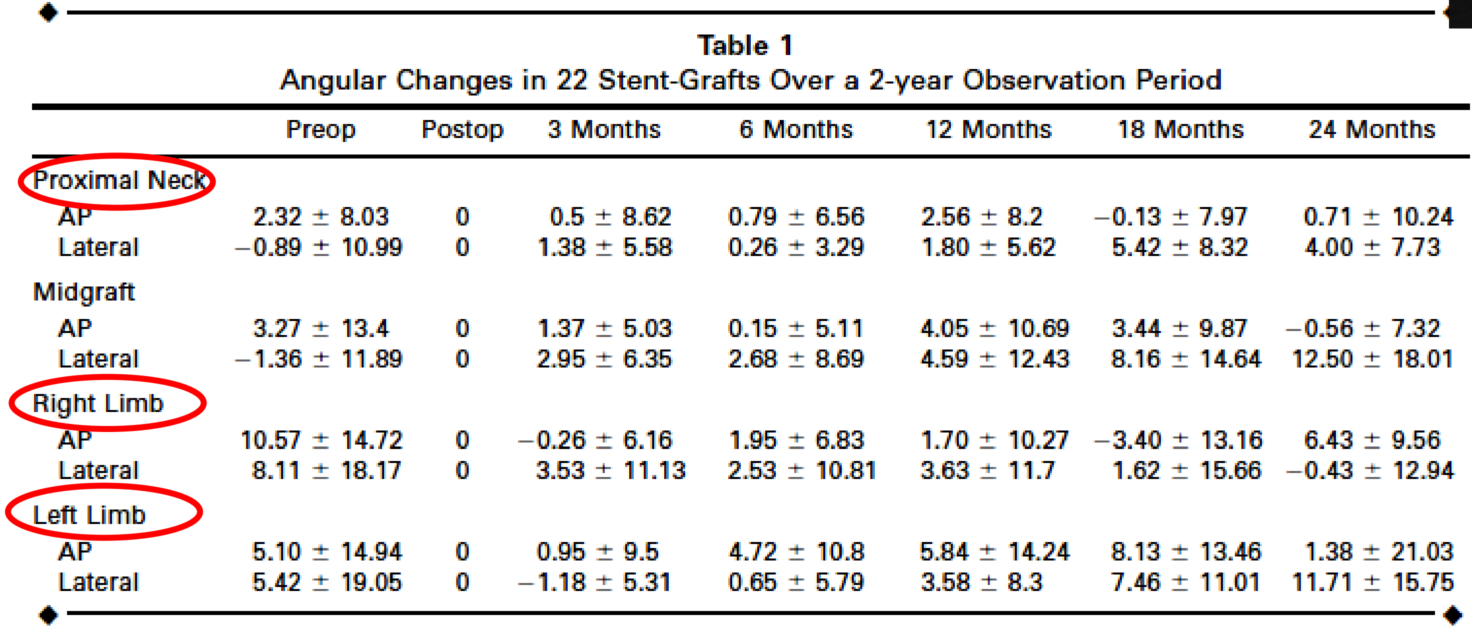


Table 1
Angular Changes in 22 Stent-Grafts Over a 2-year Observation Period

	Preop	Postop	3 Months	6 Months	12 Months	18 Months	24 Months
Proximal Neck							
AP	2.32 ± 8.03	0	0.5 ± 8.62	0.79 ± 6.56	2.56 ± 8.2	−0.13 ± 7.97	0.71 ± 10.24
Lateral	−0.89 ± 10.99	0	1.38 ± 5.58	0.26 ± 3.29	1.80 ± 5.62	5.42 ± 8.32	4.00 ± 7.73
Midgraft							
AP	3.27 ± 13.4	0	1.37 ± 5.03	0.15 ± 5.11	4.05 ± 10.69	3.44 ± 9.87	−0.56 ± 7.32
Lateral	−1.36 ± 11.89	0	2.95 ± 6.35	2.68 ± 8.69	4.59 ± 12.43	8.16 ± 14.64	12.50 ± 18.01
Right Limb							
AP	10.57 ± 14.72	0	−0.26 ± 6.16	1.95 ± 6.83	1.70 ± 10.27	−3.40 ± 13.16	6.43 ± 9.56
Lateral	8.11 ± 18.17	0	3.53 ± 11.13	2.53 ± 10.81	3.63 ± 11.7	1.62 ± 15.66	−0.43 ± 12.94
Left Limb							
AP	5.10 ± 14.94	0	0.95 ± 9.5	4.72 ± 10.8	5.84 ± 14.24	8.13 ± 13.46	1.38 ± 21.03
Lateral	5.42 ± 19.05	0	−1.18 ± 5.31	0.65 ± 5.79	3.58 ± 8.3	7.46 ± 11.01	11.71 ± 15.75

Since the very beginning of endovascular surgery, it became apparent that the aneurysm geometry changes immediately postoperatively and continues to change even after 3years, a process characterized as remodelling

Notably, these changes mirror the force and stress distribution (mechanical basis of REMODELLING)

Remodelling: decrease of angulation of infarenal neck

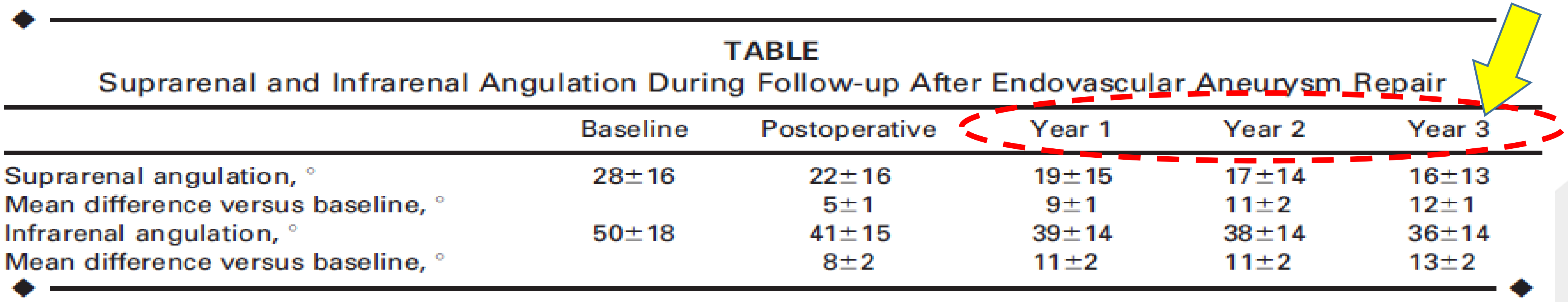
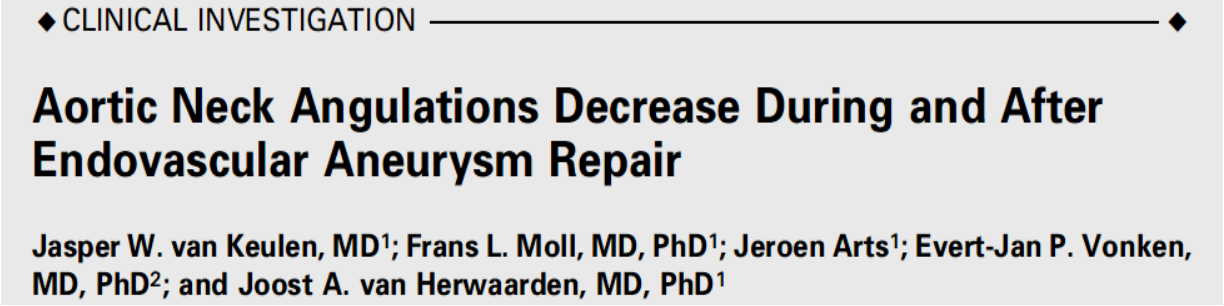


TABLE
Suprarenal and Infrarenal Angulation During Follow-up After Endovascular Aneurysm Repair

	Baseline	Postoperative	Year 1	Year 2	Year 3
Suprarenal angulation, °	28±16	22±16	19±15	17±14	16±13
Mean difference versus baseline, °		5±1	9±1	11±2	12±1
Infrarenal angulation, °	50±18	41±15	39±14	38±14	36±14
Mean difference versus baseline, °		8±2	11±2	11±2	13±2



◆ CLINICAL INVESTIGATION ◆

Aortic Neck Angulations Decrease During and After Endovascular Aneurysm Repair

Jasper W. van Keulen, MD[1]; Frans L. Moll, MD, PhD[1]; Jeroen Arts[1]; Evert-Jan P. Vonken, MD, PhD[2]; and Joost A. van Herwaarden, MD, PhD[1]

Since the very beginning of endovascular surgery, it became apparent that the aneurysm geometry changes immediately postoperatively and continues to change even after 3years, a process characterized as remodelling

Notably, these changes mirror the force and stress distribution (mechanical basis of REMODELLING)

J ENDOVASC THER
2010;17:594–598

Remodelling: decrease of iliac angulation / tortuosity

The impact of endovascular aneurysm repair on aortoiliac tortuosity and its use as a predictor of iliac limb complications

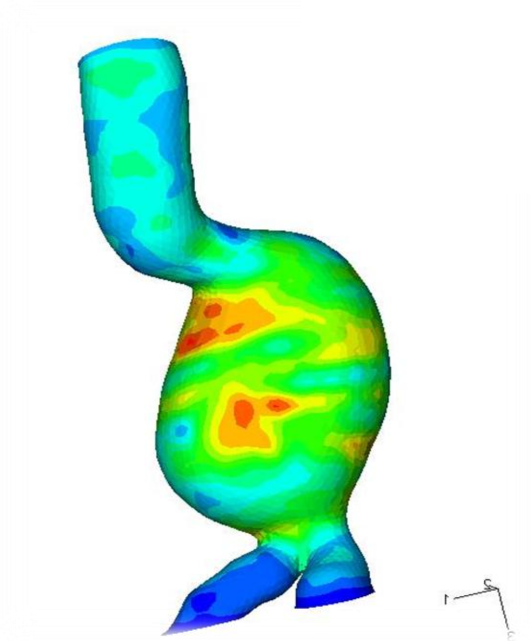
Table II. Tortuosity related to graft device implanted

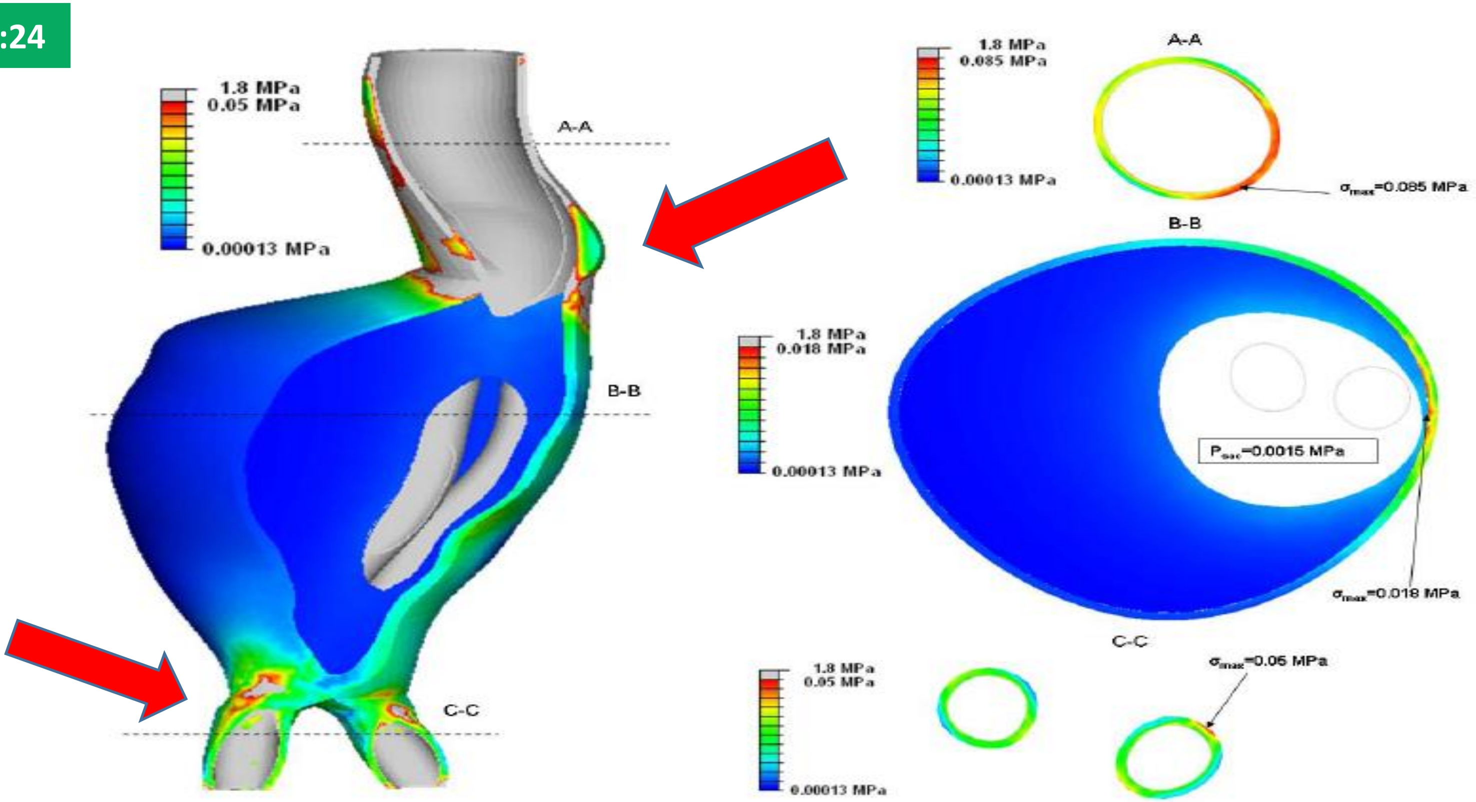
	Zenith (*n* = 40)	*Excluder* (*n* = 40)	*Endurant* (*n* = 40)
Preoperative			
Aortic	1.08 (1.01-1.48)	1.09 (1.01-1.38)	1.12 (1.01-1.54)
Right iliac	1.11 (1.02-1.35)	1.11 (1.01-1.51)	1.11 (1.02-1.35)
Left iliac	1.13 (1.01-1.51)	1.14 (1.02-1.41)	1.16 (1.00-1.61)
Postoperative			
Aortic	1.04 (1.00-1.40)	1.07 (1.01-1.31)	1.10 (1.01-1.48)
Right iliac	1.07 (1.01-1.31)	1.10 (1.01-1.48)	1.09 (1.01-1.31)
Left iliac	1.09 (1.01-1.39)	1.13 (1.01-1.40)	1.14 (1.02-1.58)

Coulston et al, JVS, 2014; 60:585-9

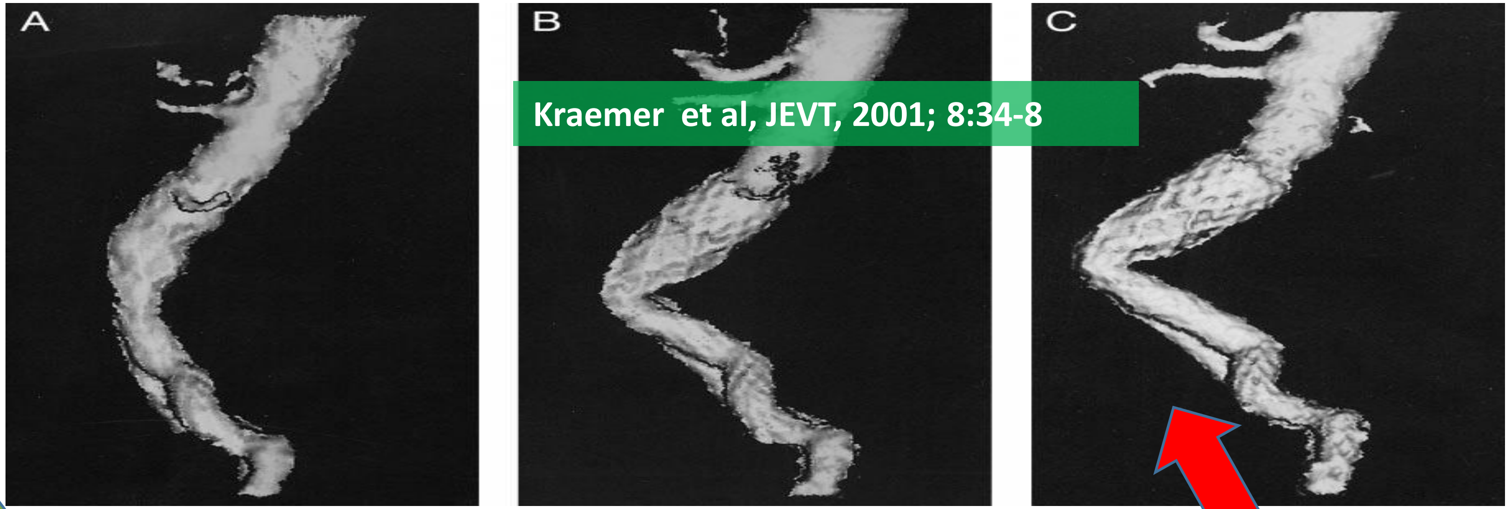
Redistribution of peak wall stress from sac to neck and iliacs postEVAR

Molony et al, J Biomed Eng Online, 2009; 8:24



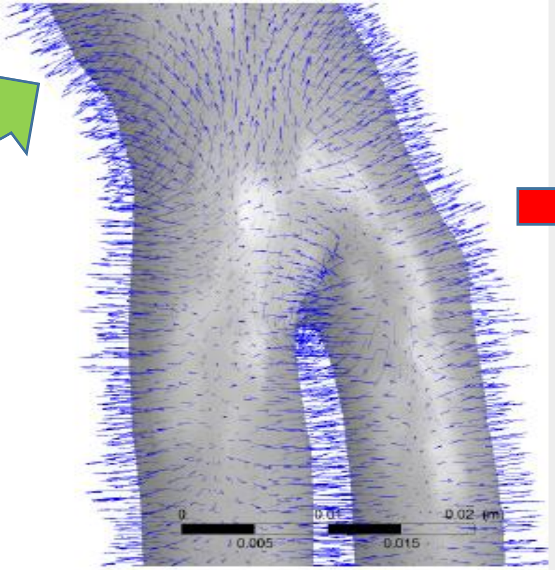


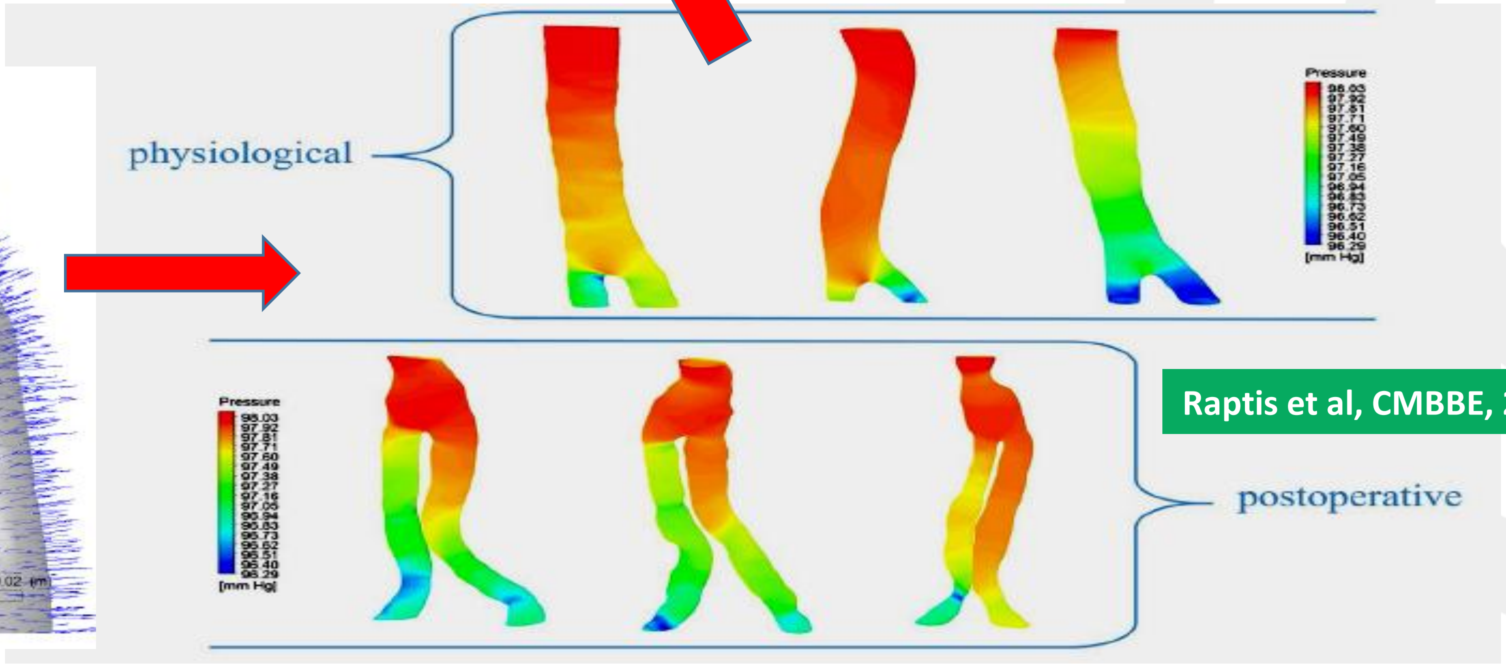
Computational studies have associated the postEVAR geometrical changes with increase of wall stress at the sealing sites (due to continuous outward radial forces) and decrease of the AAA sac stress, thus enabling shrinkage



Kraemer et al, JEVT, 2001; 8:34-8

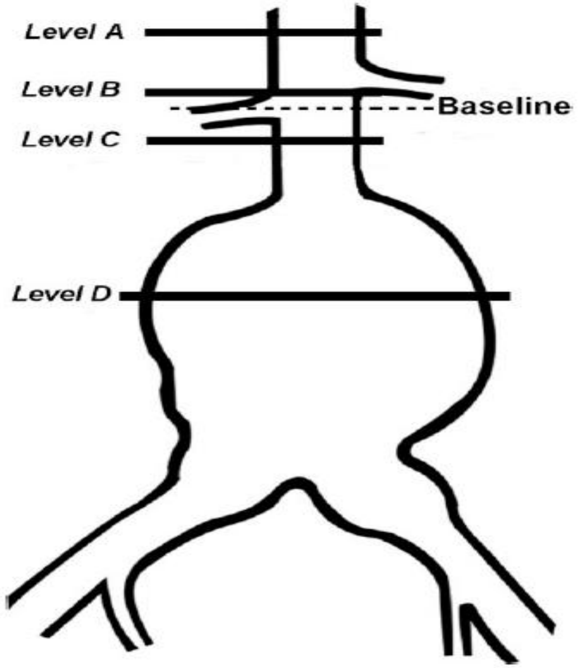
__Remodelling__:
Decrease of neck- and iliac angulation with redistribution of forces on the endograft





Raptis et al, CMBBE, 2017; 20:242-9

Aortic Compliance Following EVAR and the Influence of Different Endografts: Determination Using Dynamic MRA



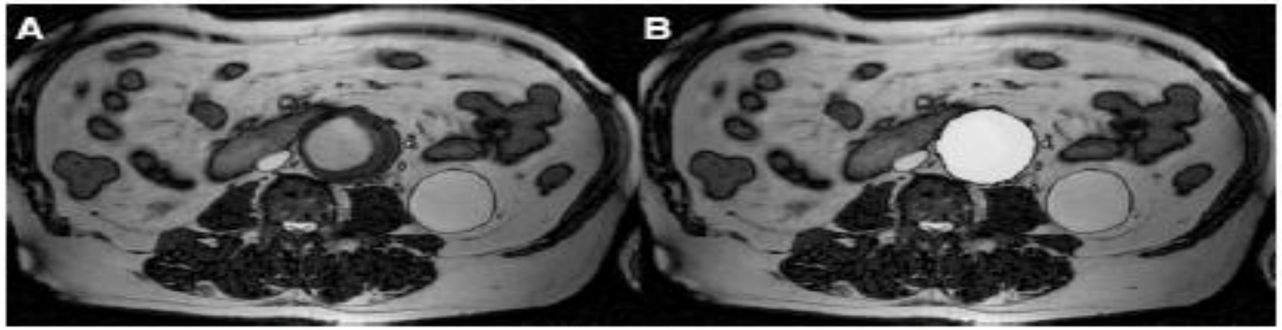


Figure 2 ◆ Representative preoperative images without (**A**) and with (**B**) automatically created segmentation of the aorta at the level of maximum aneurysm sac diameter.

Elastic modulus (Ep): measure of distensibility

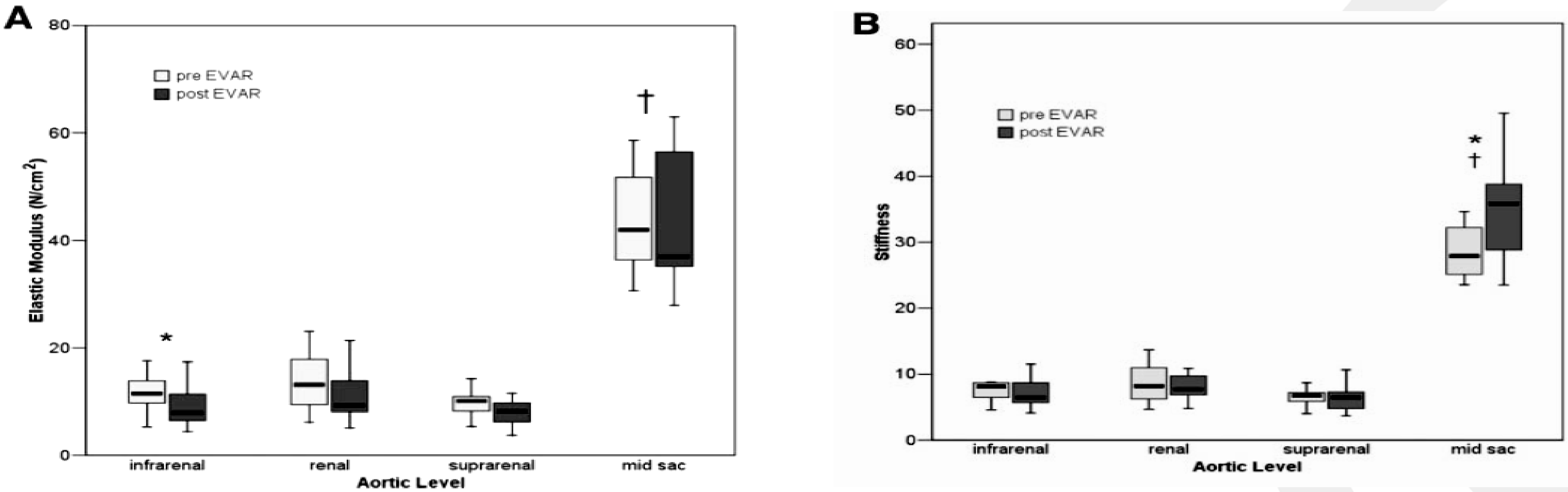
$$E_p = K\frac{P_{sys} - P_{dias}}{(D_{sys} - D_{dias})/D_{dias}} = KD_{dias}\frac{\Delta P}{\Delta D}$$

$$\beta = \ln\left(\frac{P_{sys}}{P_{dias}}\right)\frac{D_{dias}}{\Delta D}.$$

Stiffness (β): expresses the viscoelastic behavior of aortic wall

J ENDOVASC THER
2006;13:406–414

Mechanical changes of aortic wall after EVAR



Aortic compliance is decrased directly after endograft implantation (stiffness increase)

J ENDOVASC THER
2006;13:406–414

Mechanical changes of aortic wall after EVAR

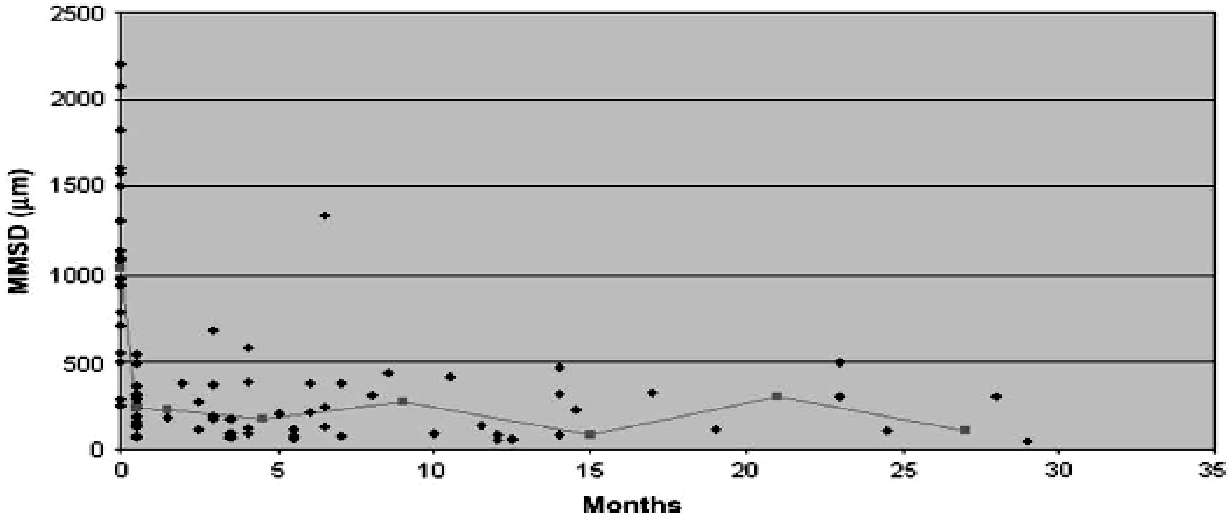
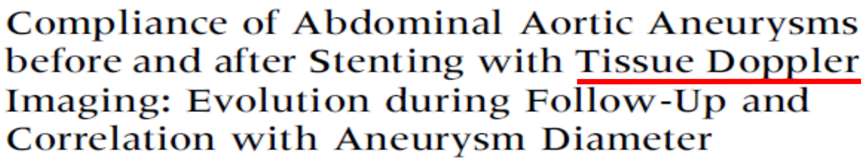


Fig. 2. Evolution of MMSD during follow-up after successful endovascular repair, showing a significant decrease between the preoperative measurement and the early control before discharge but not during later follow-up.

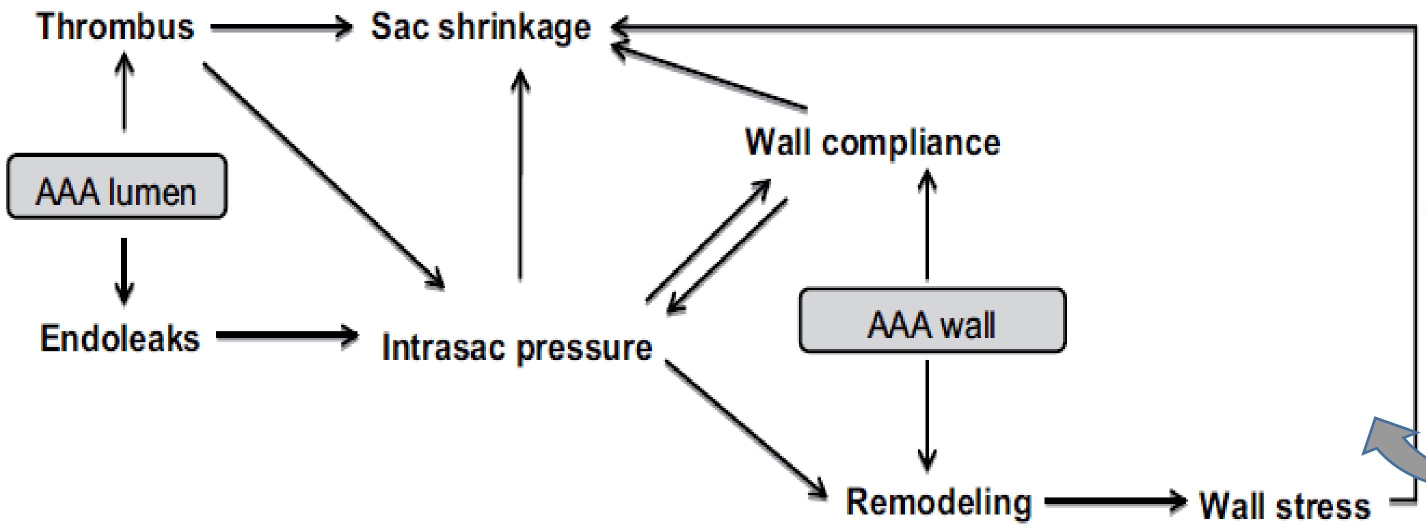

Compliance of Abdominal Aortic Aneurysms
before and after Stenting with Tissue Doppler
Imaging: Evolution during Follow-Up and
Correlation with Aneurysm Diameter

- ✓ *Aortic compliance decreases immediately after the endograft implantation (increase of stiffness) but stays steady during follow-up*
- ✓ *Aortic mechanical changes post-EVAR are not related to the decrease rate of aneurysm diameter.*

Long et al, EJVES, 2009; 23:49-59

Mechanical changes of Aortic wall after EVAR

AAA SAC +ENDOGRAFT = COMBINED SYSTEM



Thrombus

Sac shrinkage

AAA lumen

Wall compliance

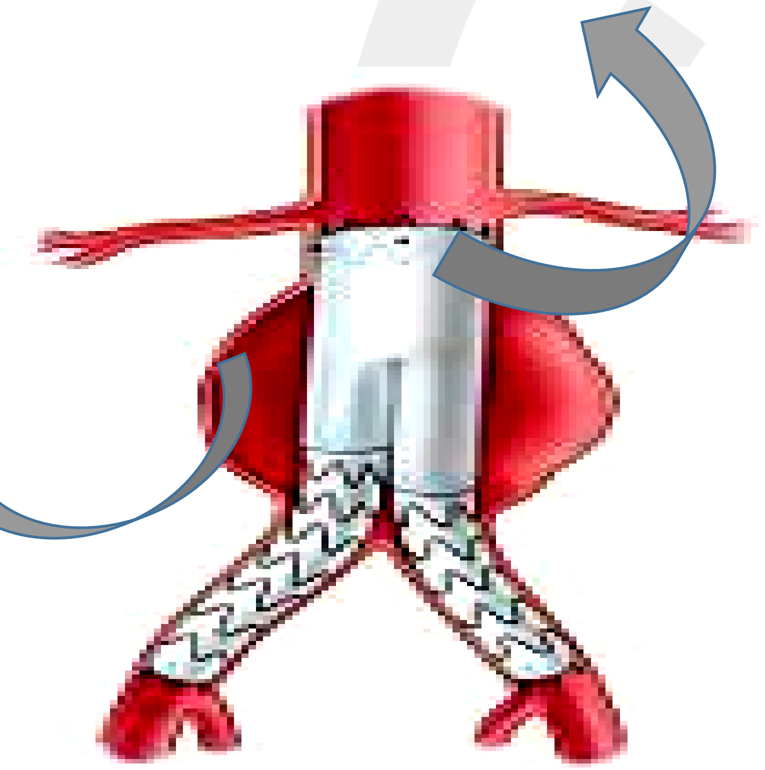
Endoleaks

Intrasac pressure

AAA wall

Remodeling

Wall stress



Conformational changes

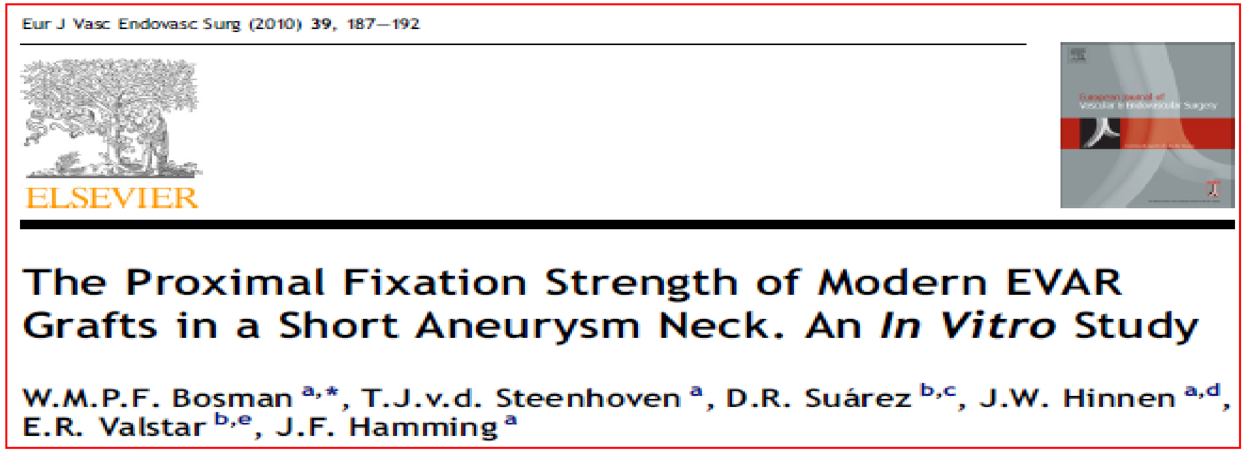
Georgakarakos et al, Vasc Med 2012; 17:168-73

Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

PERFORMANCE OF ENDOGRAFS

INFRARENAL NECK

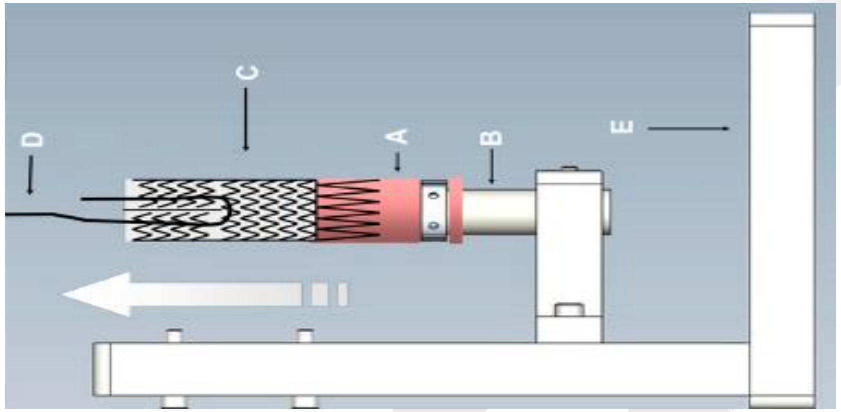
- ✓Fixation modes
- ✓Central fixation
- ✓Distribution of forces
- ✓Improvements & modifications

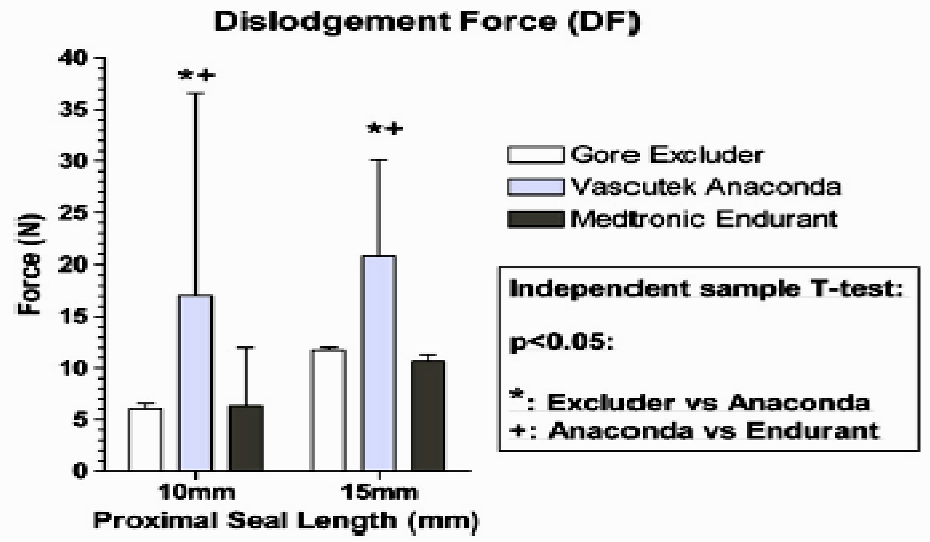

Eur J Vasc Endovasc Surg (2010) 39, 187–192

ELSEVIER

The Proximal Fixation Strength of Modern EVAR Grafts in a Short Aneurysm Neck. An *In Vitro* Study

W.M.P.F. Bosman [a,*], T.J.v.d. Steenhoven [a], D.R. Suárez [b,c], J.W. Hinnen [a,d], E.R. Valstar [b,e], J.F. Hamming [a]





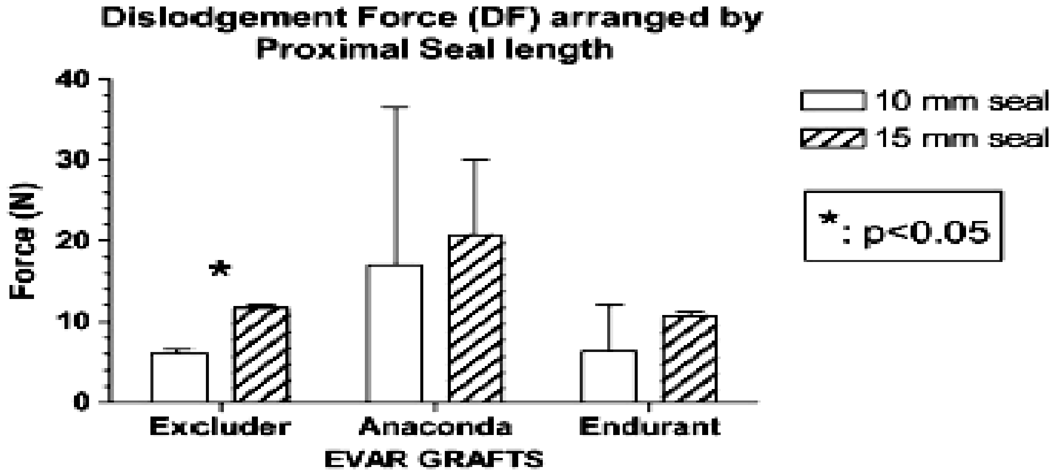
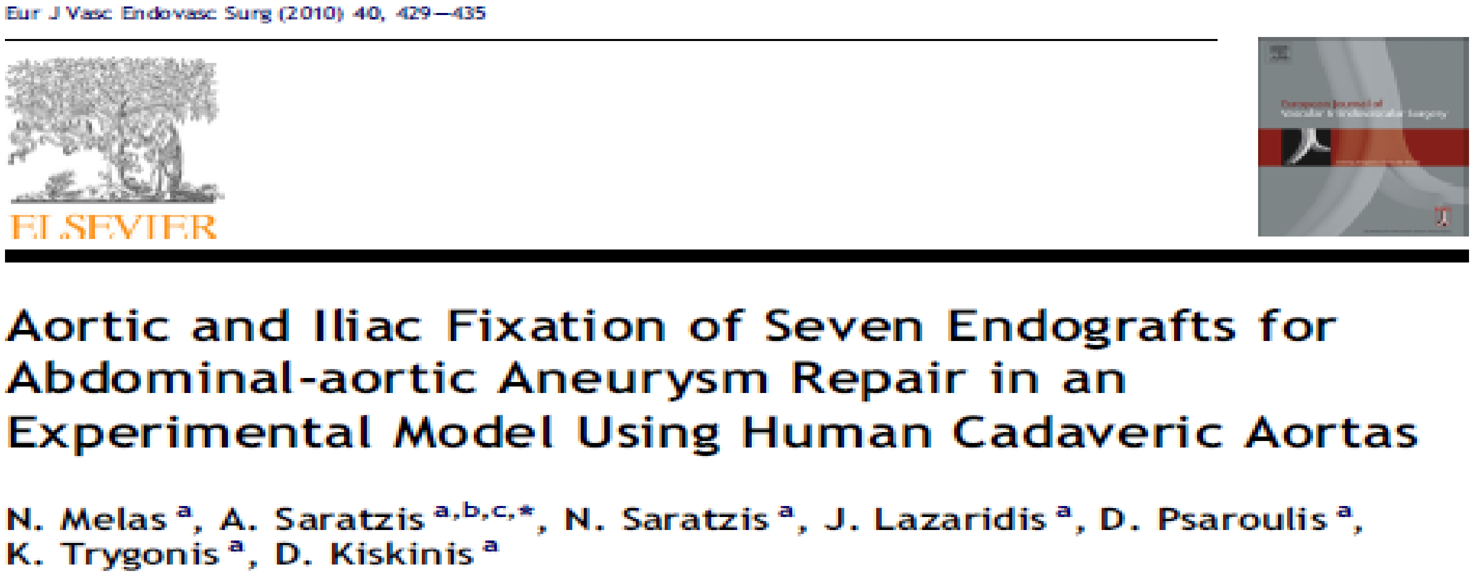


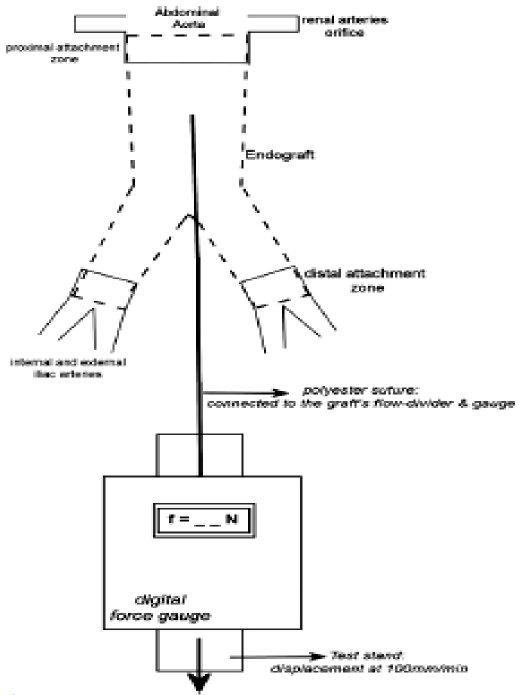
Figure 2 The endografts used in this study: A. Gore Excluder, B. Vascutek Anaconda and C. Medtronic Endurant.



Eur J Vasc Endovasc Surg (2010) 40, 429—435

Aortic and Iliac Fixation of Seven Endografts for Abdominal-aortic Aneurysm Repair in an Experimental Model Using Human Cadaveric Aortas

N. Melas [a], A. Saratzis [a,b,c,*], N. Saratzis [a], J. Lazaridis [a], D. Psaroulis [a],
K. Trygonis [a], D. Kiskinis [a]



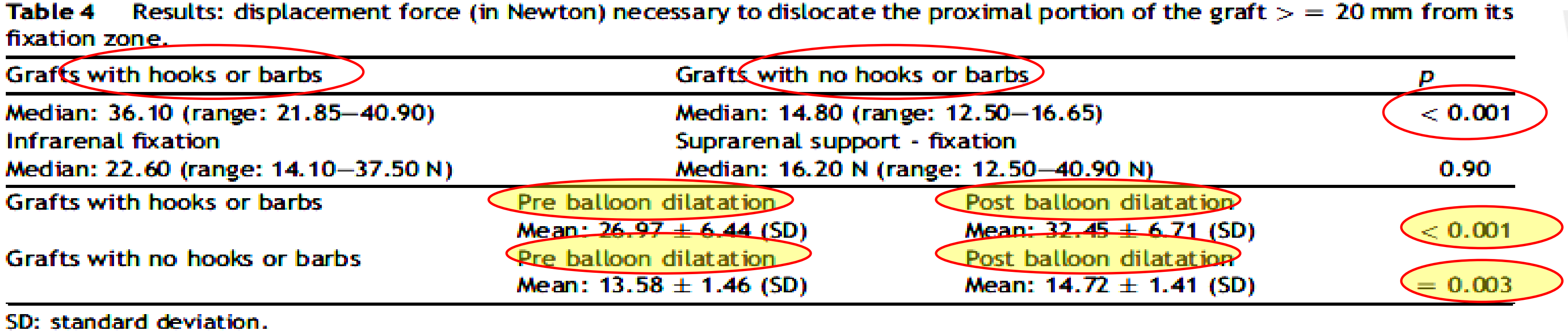


Table 4 Results: displacement force (in Newton) necessary to dislocate the proximal portion of the graft > = 20 mm from its fixation zone.

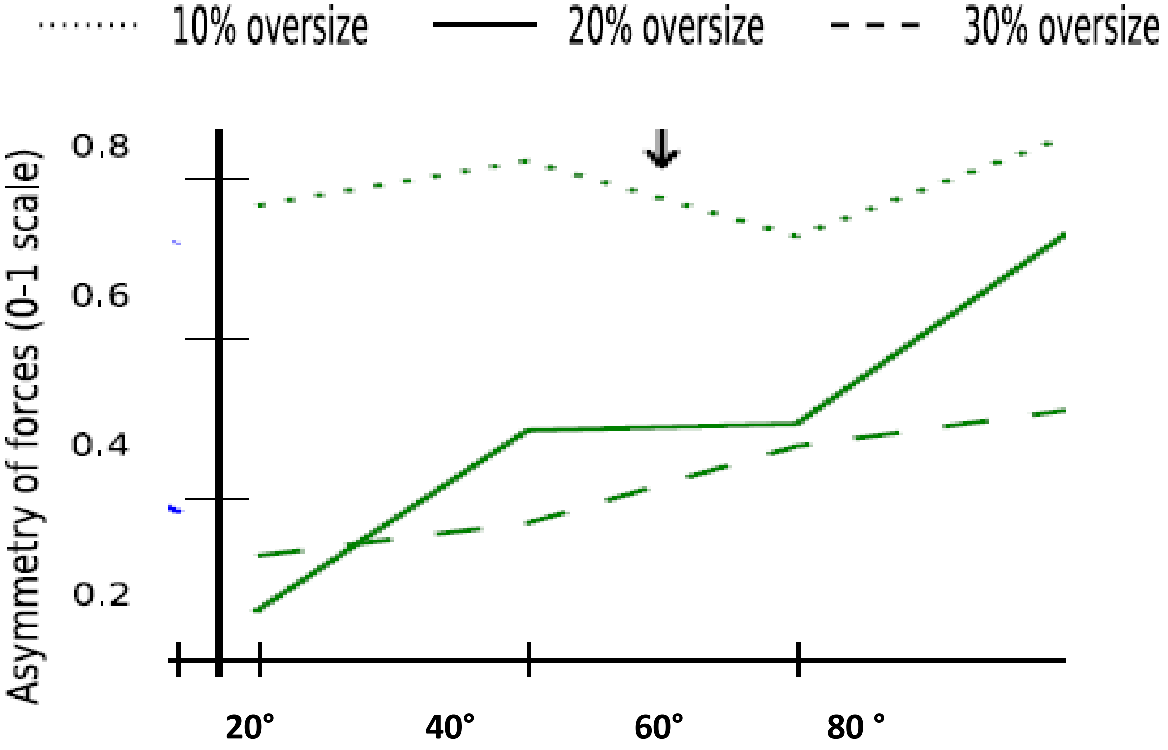
Grafts with hooks or barbs		Grafts with no hooks or barbs	p
Median: 36.10 (range: 21.85–40.90)		Median: 14.80 (range: 12.50–16.65)	< 0.001
Infrarenal fixation Median: 22.60 (range: 14.10–37.50 N)		Suprarenal support - fixation Median: 16.20 N (range: 12.50–40.90 N)	0.90
Grafts with hooks or barbs	Pre balloon dilatation Mean: 26.97 ± 6.44 (SD)	Post balloon dilatation Mean: 32.45 ± 6.71 (SD)	< 0.001
Grafts with no hooks or barbs	Pre balloon dilatation Mean: 13.58 ± 1.46 (SD)	Post balloon dilatation Mean: 14.72 ± 1.41 (SD)	= 0.003

SD: standard deviation.

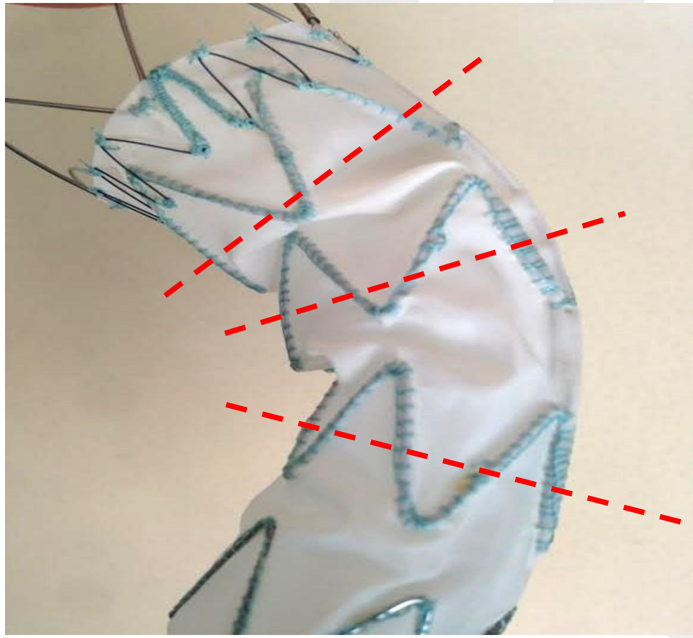
Conclusions: Devices with fixation hooks displayed higher proximal fixation. Moulding-balloon dilatation increased proximal and distal fixation. Suprarenal support did not affect proximal fixation.

Factors influencing stress distribution at the infrarenal neck

Low oversizing (i.e., 10%) is associated with significant asymmetry of forces at the infrarenal neck

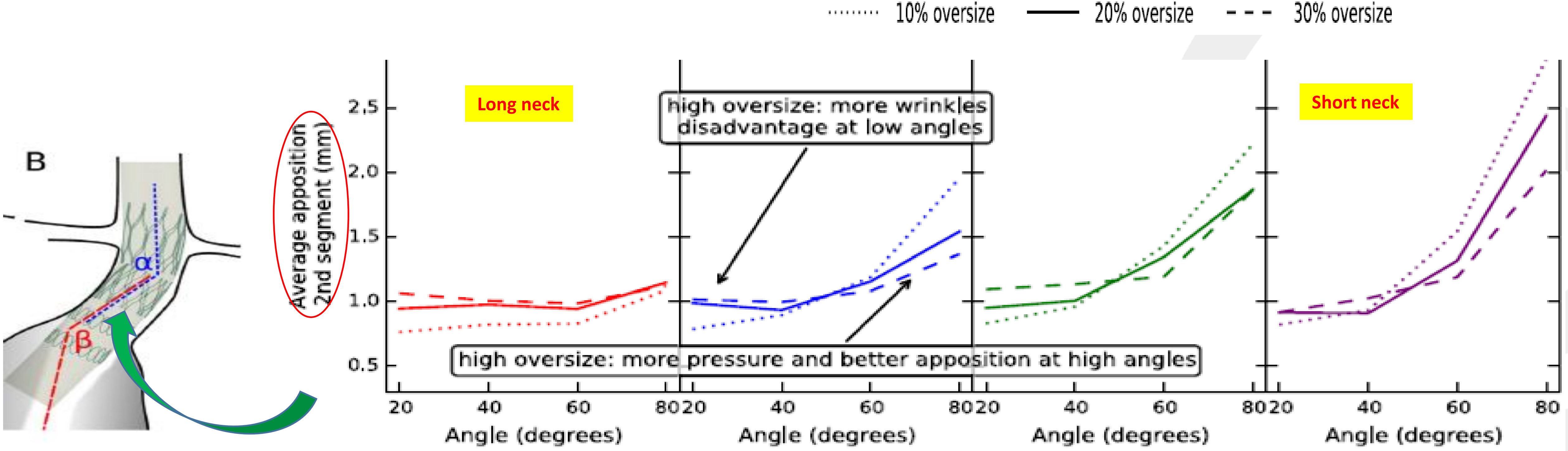


De Bock et al, Med Eng Phys 2014; 36: 1567-76



Factors influencing stress distribution at the infrarenal neck

The stent apposition on the infarenal neck is determined by the length and angulation of the neck as well as the degree of oversizing



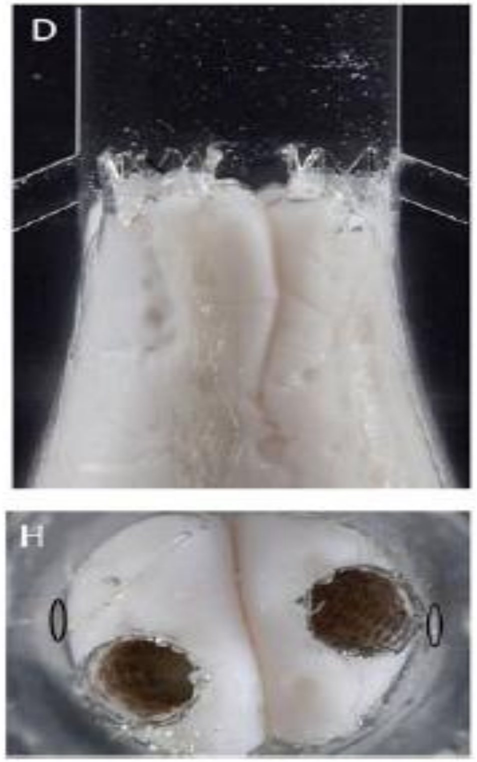
high oversize: more wrinkles disadvantage at low angles

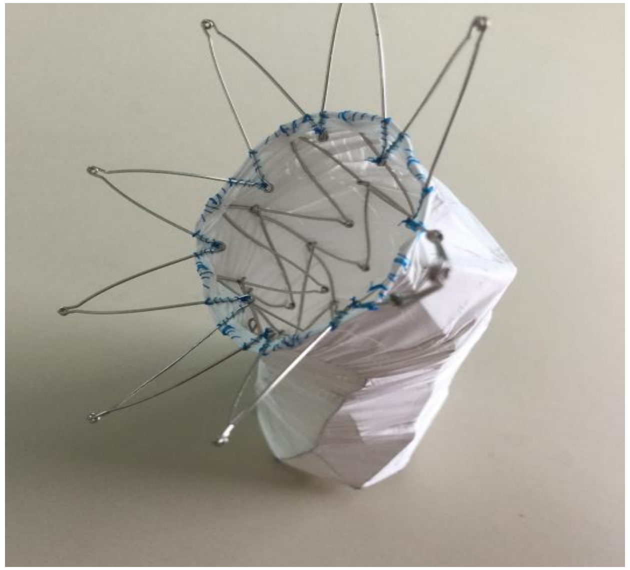
high oversize: more pressure and better apposition at high angles

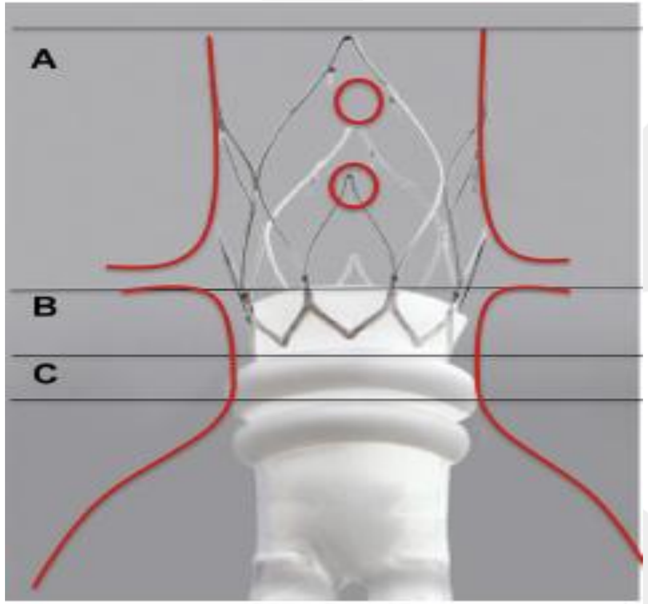
De Bock et al, Med Eng Phys 2014; 36: 1567-76

Factors influencing stress distribution at the infrarenal neck

Newly introduced Nitinol-free technologies and sealing patterns claim to decrease the continuous outward pressure on the infrarenal neck, thereby prohibiting the neck enlargement postEVAR







De Donato et al., JVS 2016; 63:8-15
Börsen et al., JVS 2017; 24:677-87
Savlovskis et al., JVS 2017; 62:541-9

Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

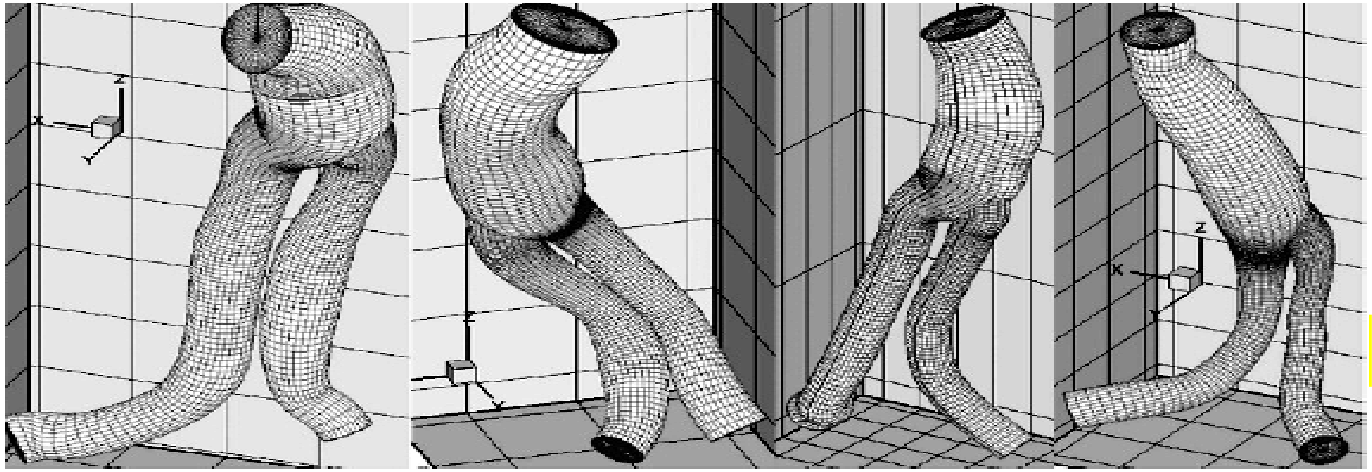
PERFORMANCE OF ENDOGRAFTS

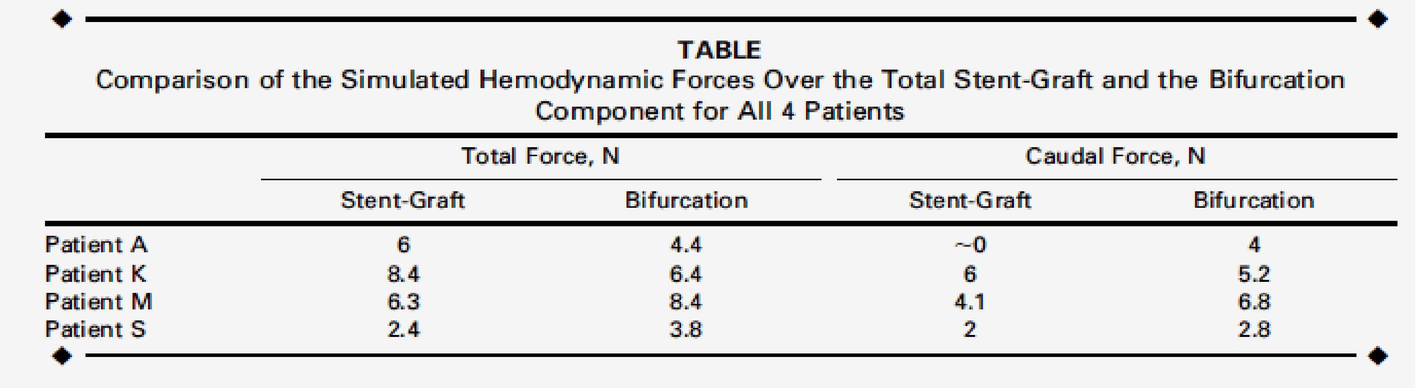
ILIAC LIMBS

- ✓Distal fixation
- ✓Distribution of forces
- ✓Desings and mechanisms
- ✓endoleaks
- ✓The role of geometry
- ✓improvements & modifications

Distribution of forces on endografts

The greatest percentage of forces is applied at the bifurcation of endografts

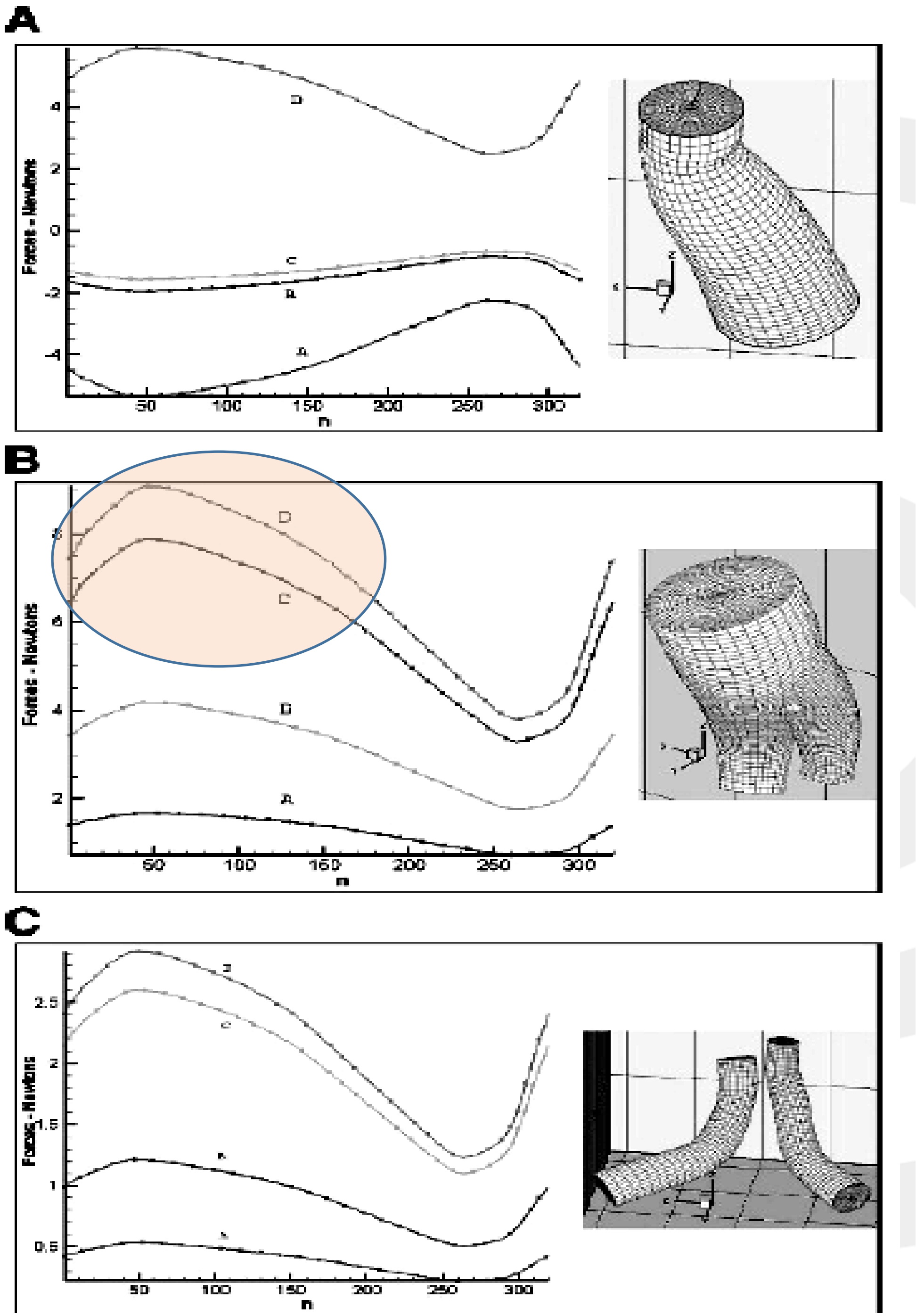




TABLE

Comparison of the Simulated Hemodynamic Forces Over the Total Stent-Graft and the Bifurcation Component for All 4 Patients

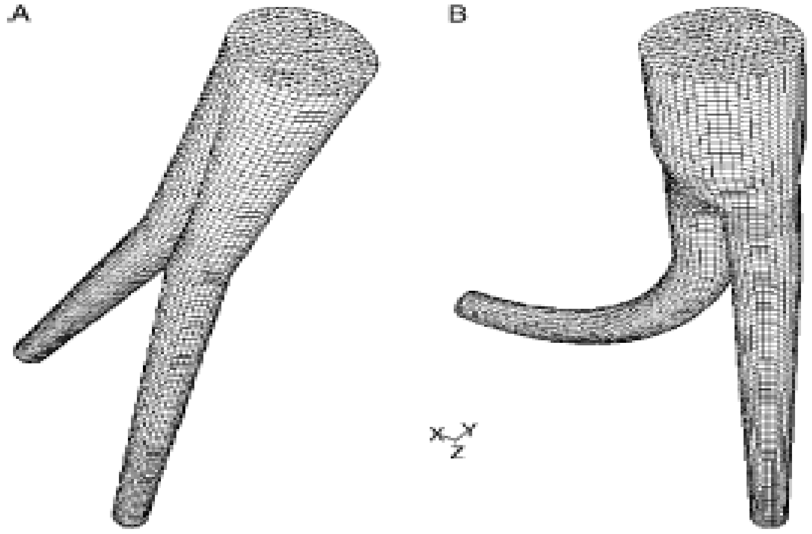
	Total Force, N		Caudal Force, N	
	Stent-Graft	Bifurcation	Stent-Graft	Bifurcation
Patient A	6	4.4	~0	4
Patient K	8.4	6.4	6	5.2
Patient M	6.3	8.4	4.1	6.8
Patient S	2.4	3.8	2	2.8

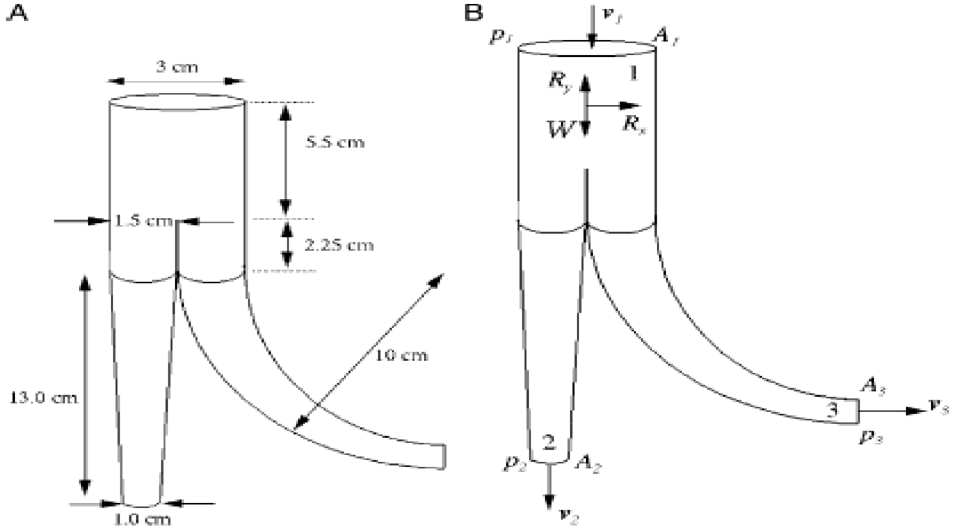


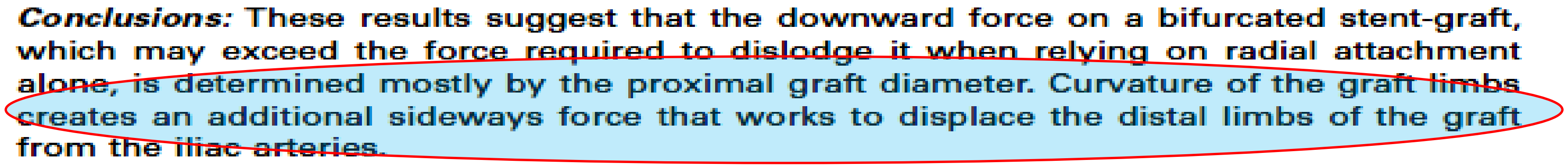
Howell et al, JEVT, 2007; 14:138-43

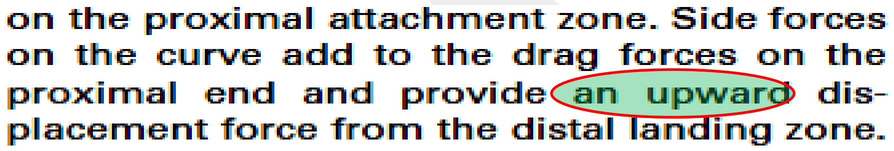
Distribution of forces at the iliac limbs of endografts

The curvature of iliac limbs creates extra displacement forces at the iliac limbs






Conclusions: These results suggest that the downward force on a bifurcated stent-graft, which may exceed the force required to dislodge it when relying on radial attachment alone, is determined mostly by the proximal graft diameter. Curvature of the graft limbs creates an additional sideways force that works to displace the distal limbs of the graft from the iliac arteries.


on the proximal attachment zone. Side forces on the curve add to the drag forces on the proximal end and provide an upward displacement force from the distal landing zone.

Liffman et al, JEVT 2001; 8:358-71

Estimating the magnitude of forces at the iliac limbs of endografts

Experimental setup

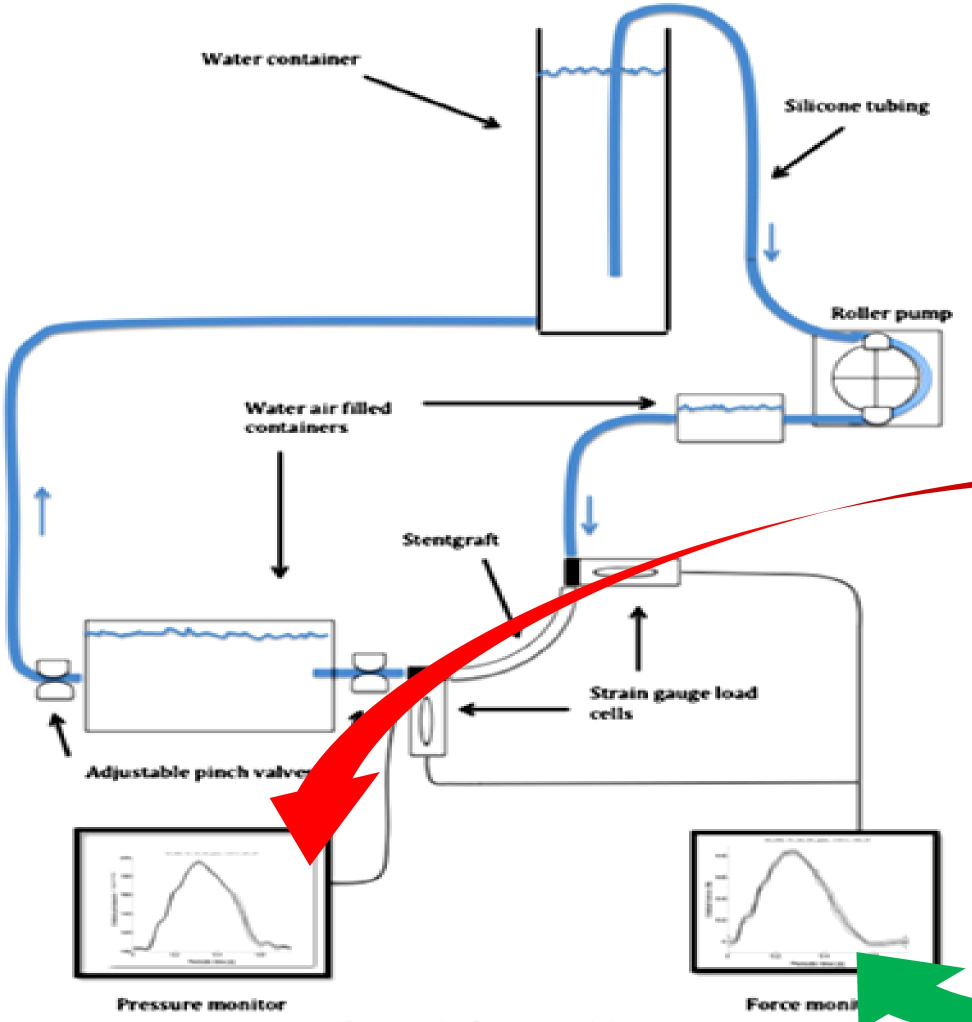


Figure 1. Perfusion model.

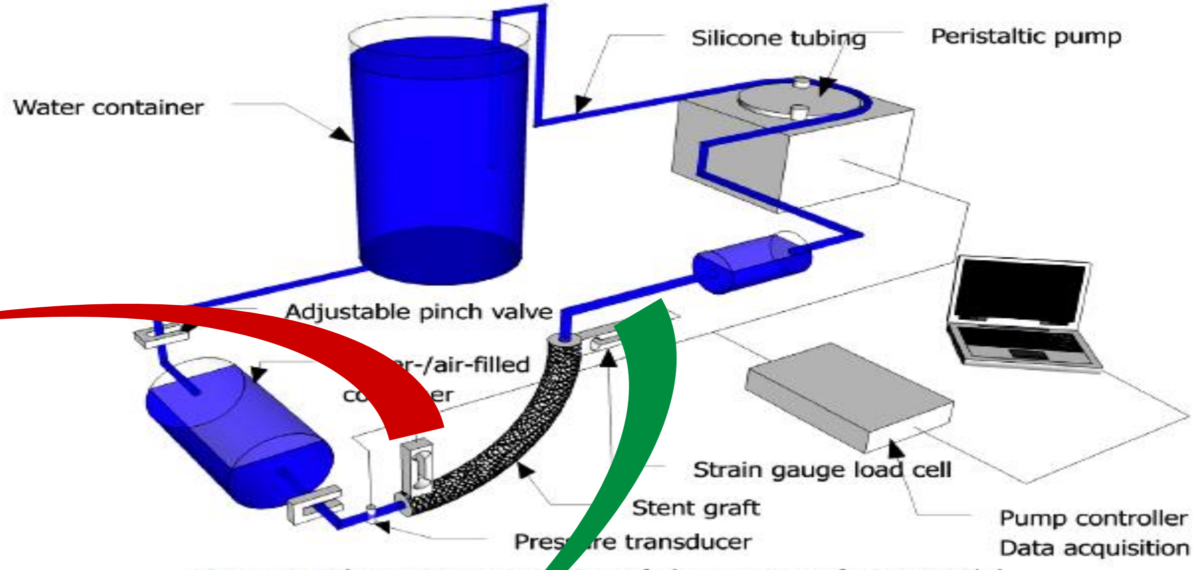
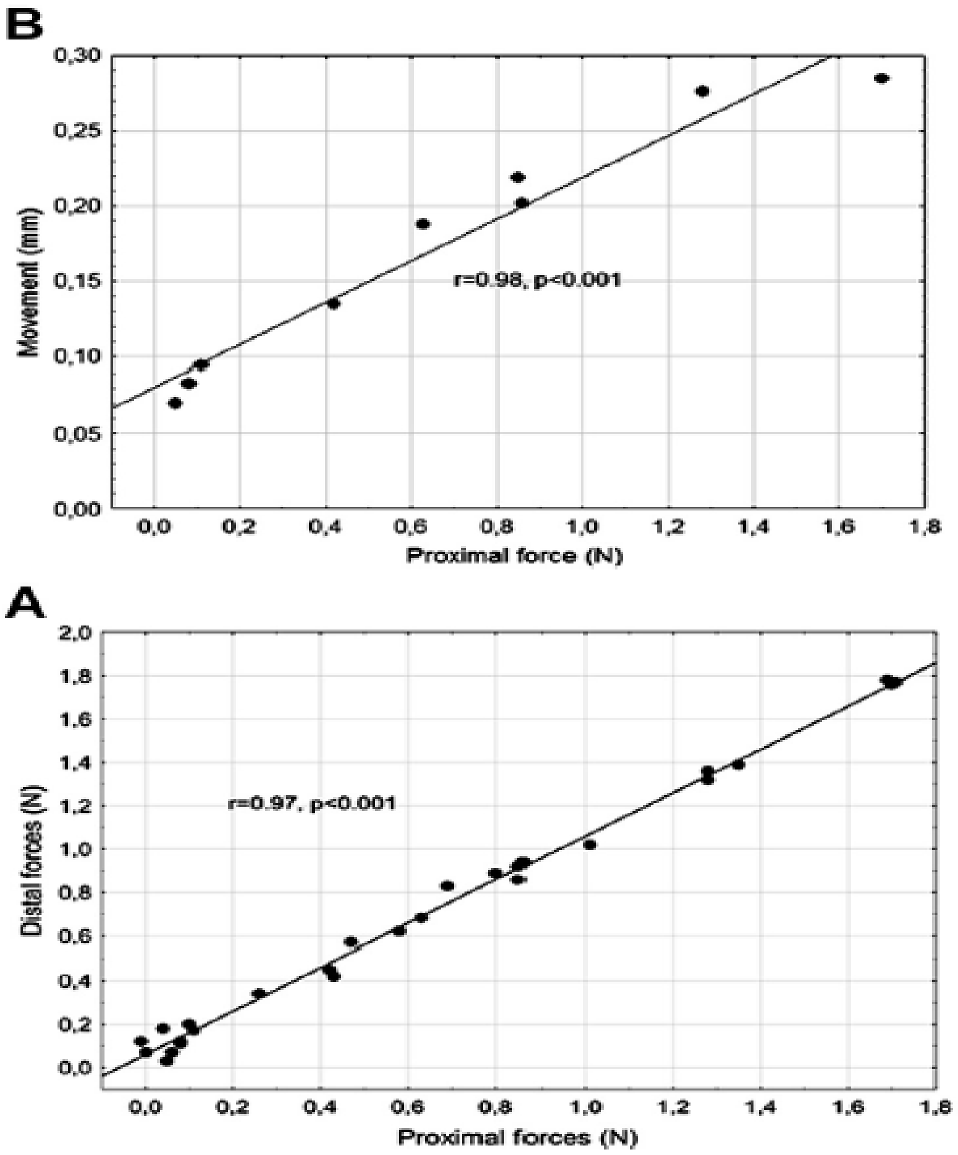


Figure 1. Schematic presen ation of the aortic perfusion model.

Roos et al, EJVES 2014; 47:262-7
Roos et al, EJVES 2016; 52: 150-6

Estimating the magnitude of forces at the iliac limbs of endografts

- ✓ Pulsatile flow creates movements in the unsupported mid-part of iliac limbs
- ✓ Iliac angulation increases the movements & forces applied on iliacs
- ✓ The greater the pressure, the greater those forces and movements



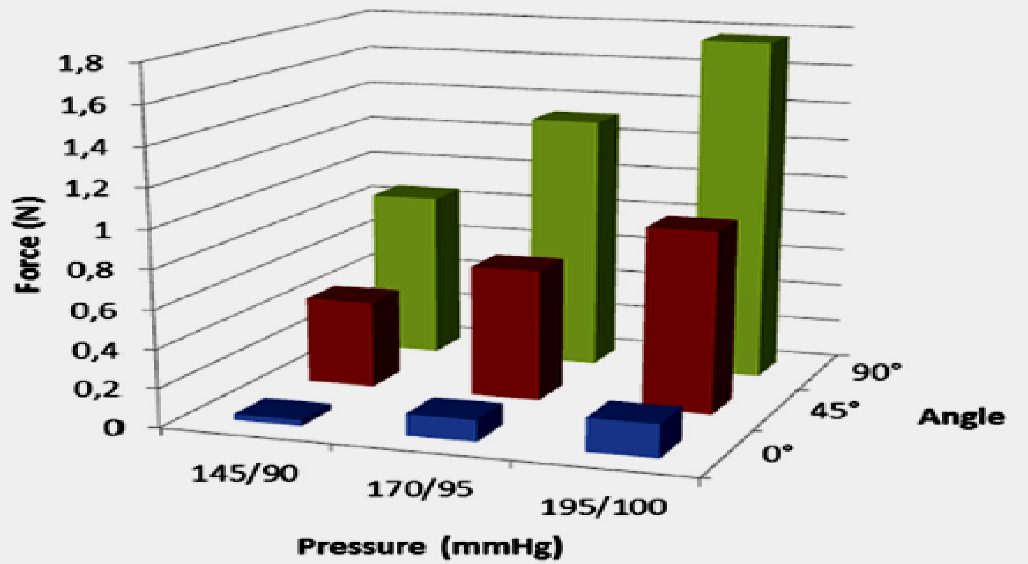
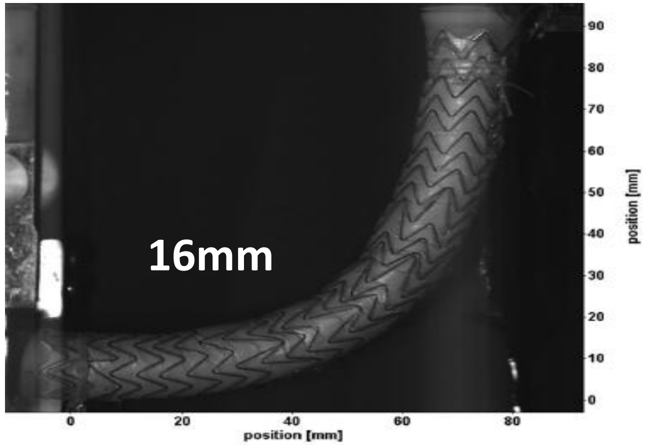
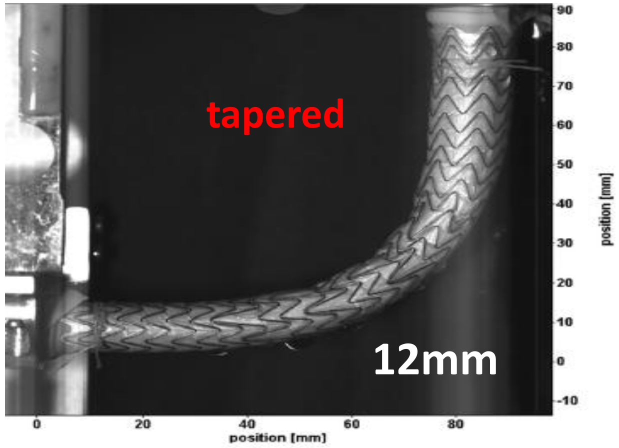
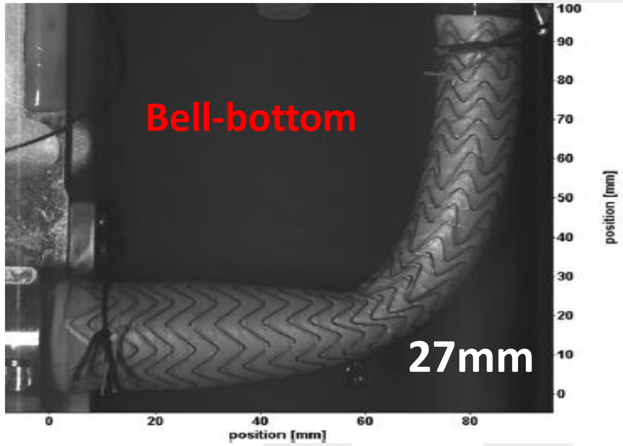


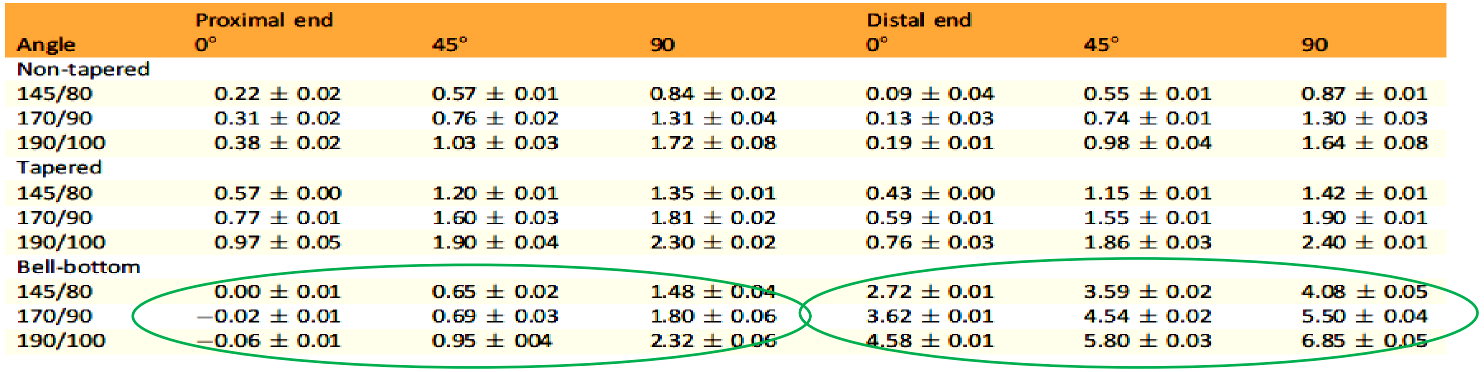
Figure 3. Peak force at the distal strain gauge cell at 80 b.p.m. at different perfusion pressures and stent graft angles.

Estimating the magnitude of forces at the iliac limbs of endografts









Angle	Proximal end 0°	45°	90	Distal end 0°	45°	90
Non-tapered						
145/80	0.22 ± 0.02	0.57 ± 0.01	0.84 ± 0.02	0.09 ± 0.04	0.55 ± 0.01	0.87 ± 0.01
170/90	0.31 ± 0.02	0.76 ± 0.02	1.31 ± 0.04	0.13 ± 0.03	0.74 ± 0.01	1.30 ± 0.03
190/100	0.38 ± 0.02	1.03 ± 0.03	1.72 ± 0.08	0.19 ± 0.01	0.98 ± 0.04	1.64 ± 0.08
Tapered						
145/80	0.57 ± 0.00	1.20 ± 0.01	1.35 ± 0.01	0.43 ± 0.00	1.15 ± 0.01	1.42 ± 0.01
170/90	0.77 ± 0.01	1.60 ± 0.03	1.81 ± 0.02	0.59 ± 0.01	1.55 ± 0.01	1.90 ± 0.01
190/100	0.97 ± 0.05	1.90 ± 0.04	2.30 ± 0.02	0.76 ± 0.03	1.86 ± 0.03	2.40 ± 0.01
Bell-bottom						
145/80	0.00 ± 0.01	0.65 ± 0.02	1.48 ± 0.04	2.72 ± 0.01	3.59 ± 0.02	4.08 ± 0.05
170/90	−0.02 ± 0.01	0.69 ± 0.03	1.80 ± 0.06	3.62 ± 0.01	4.54 ± 0.02	5.50 ± 0.04
190/100	−0.06 ± 0.01	0.95 ± 004	2.32 ± 0.06	4.58 ± 0.01	5.80 ± 0.03	6.85 ± 0.05

- ✓ The generated forces are particularly higher at the distal end of bell-bottom grafts
- ✓Need for more vigilant surveillance?

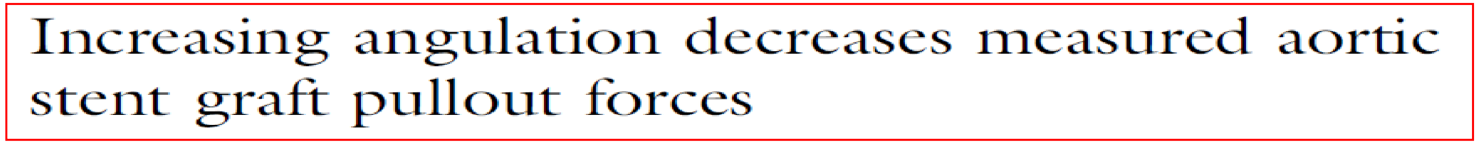
Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

PERFORMANCE OF ENDOGRAFTS

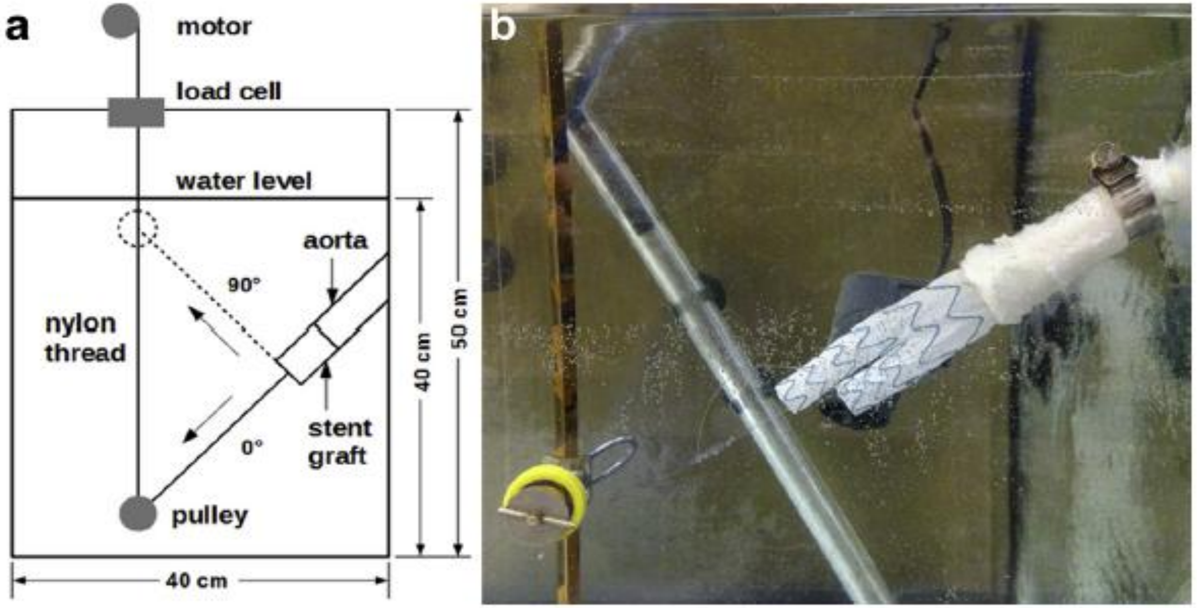
GEOMETRY

- ✓Infrarenal neck
- ✓Iliac limbs
- ✓Curvature of endografts

Factors influencing the pull-out forces predisposing to migration



Increasing angulation decreases measured aortic stent graft pullout forces



Pullout forces decrease with increasing angle
Therefore suprarenal stent with anchors is helpful

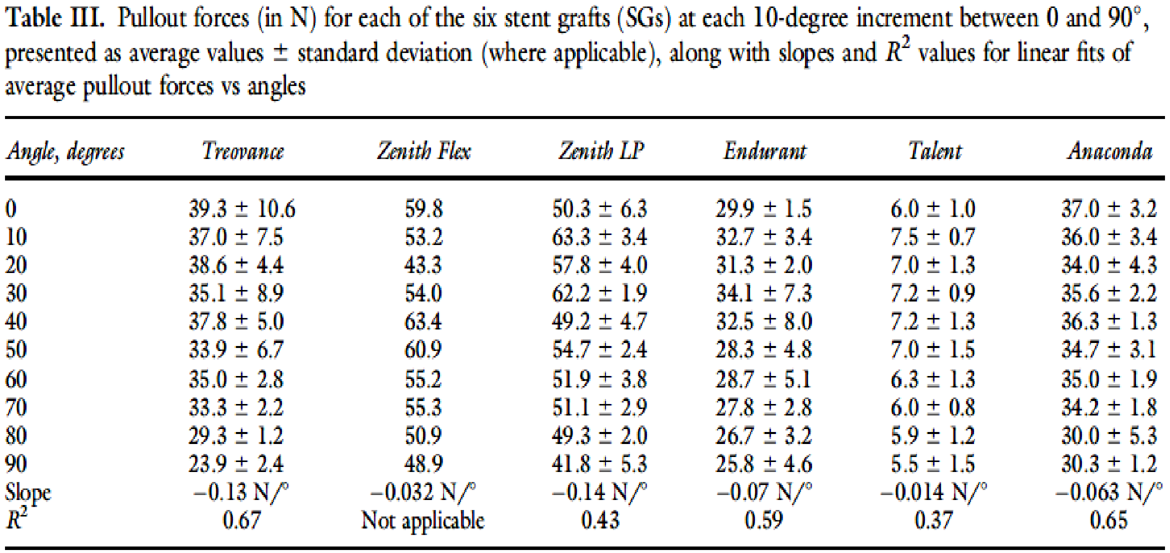
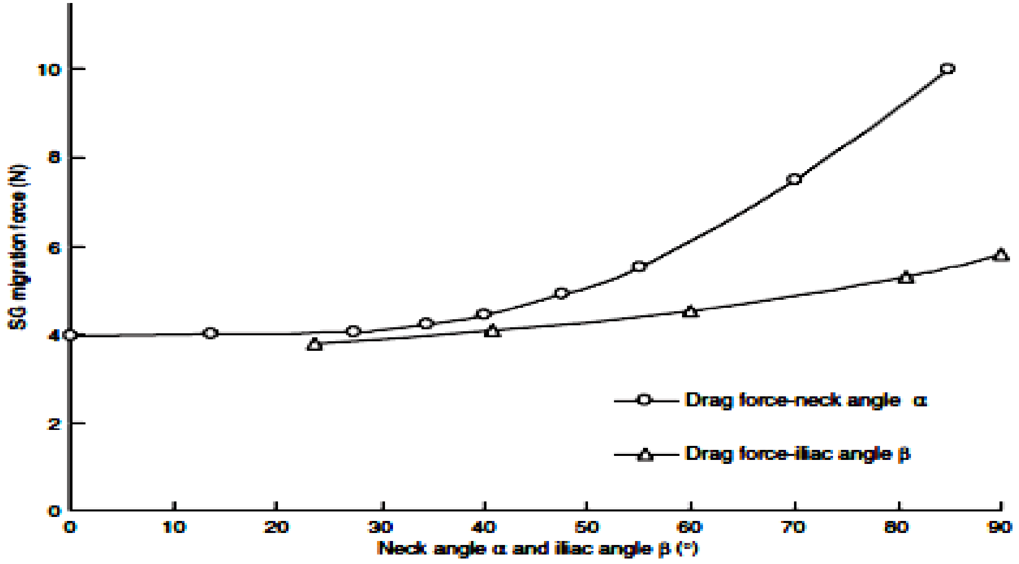


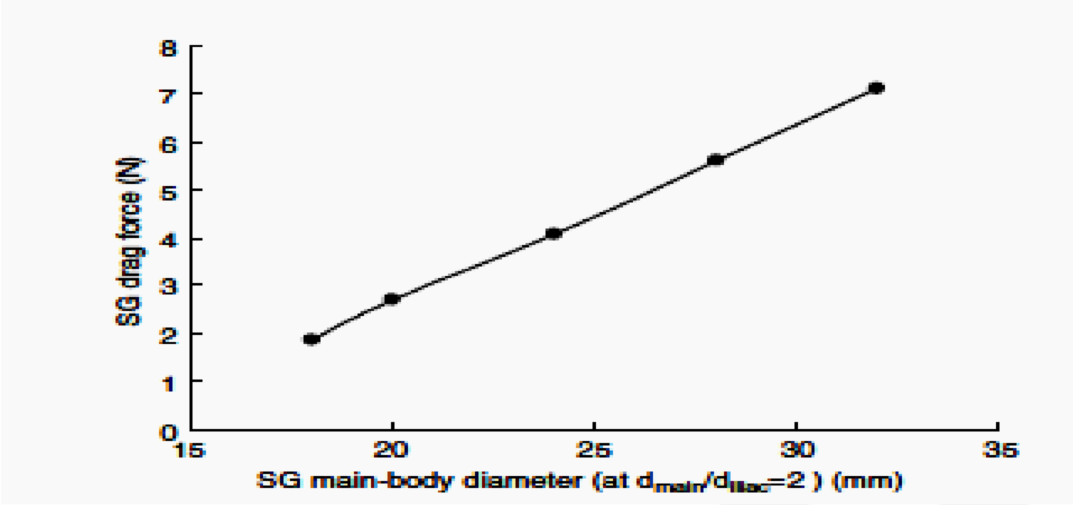
Table III. Pullout forces (in N) for each of the six stent grafts (SGs) at each 10-degree increment between 0 and 90°, presented as average values ± standard deviation (where applicable), along with slopes and R^2 values for linear fits of average pullout forces vs angles

Angle, degrees	*Treovance*	*Zenith Flex*	*Zenith LP*	*Endurant*	*Talent*	*Anaconda*
0	39.3 ± 10.6	59.8	50.3 ± 6.3	29.9 ± 1.5	6.0 ± 1.0	37.0 ± 3.2
10	37.0 ± 7.5	53.2	63.3 ± 3.4	32.7 ± 3.4	7.5 ± 0.7	36.0 ± 3.4
20	38.6 ± 4.4	43.3	57.8 ± 4.0	31.3 ± 2.0	7.0 ± 1.3	34.0 ± 4.3
30	35.1 ± 8.9	54.0	62.2 ± 1.9	34.1 ± 7.3	7.2 ± 0.9	35.6 ± 2.2
40	37.8 ± 5.0	63.4	49.2 ± 4.7	32.5 ± 8.0	7.2 ± 1.3	36.3 ± 1.3
50	33.9 ± 6.7	60.9	54.7 ± 2.4	28.3 ± 4.8	7.0 ± 1.5	34.7 ± 3.1
60	35.0 ± 2.8	55.2	51.9 ± 3.8	28.7 ± 5.1	6.3 ± 1.3	35.0 ± 1.9
70	33.3 ± 2.2	55.3	51.1 ± 2.9	27.8 ± 2.8	6.0 ± 0.8	34.2 ± 1.8
80	29.3 ± 1.2	50.9	49.3 ± 2.0	26.7 ± 3.2	5.9 ± 1.2	30.0 ± 5.3
90	23.9 ± 2.4	48.9	41.8 ± 5.3	25.8 ± 4.6	5.5 ± 1.5	30.3 ± 1.2
Slope	−0.13 N/°	−0.032 N/°	−0.14 N/°	−0.07 N/°	−0.014 N/°	−0.063 N/°
R^2	0.67	Not applicable	0.43	0.59	0.37	0.65

Rahmani et al, J Vasc Surg 2016; 63:493-9

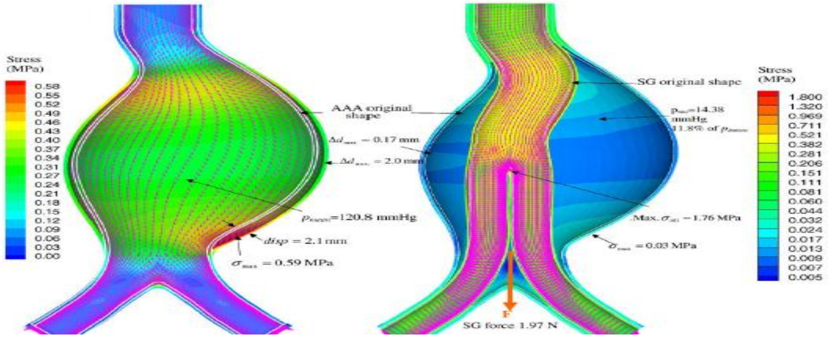
Geometric factors affecting displacement forces on endografts

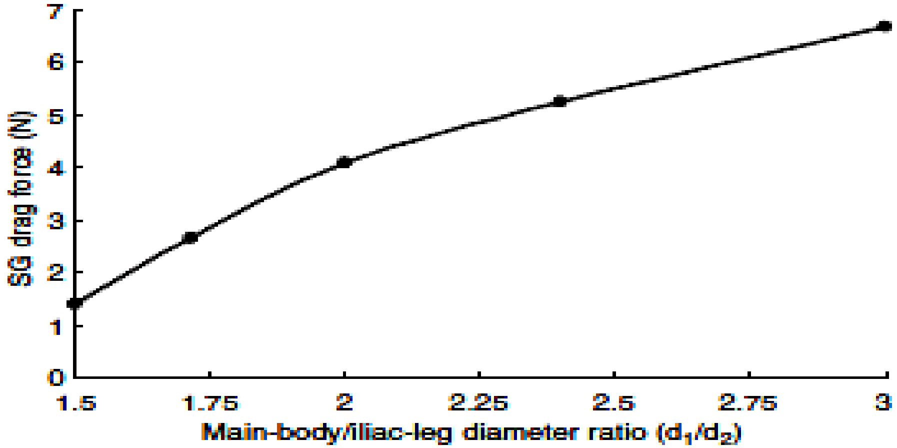




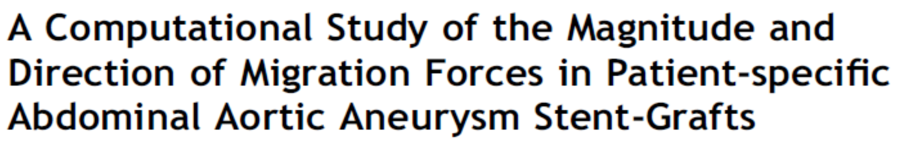
Li & Kleinstreuer, J Biomech, 2006; 39: 2264-73

✓*Neck angulation*
✓*Inlet diameter*
✓*Diameter ratio of inlet/outlet (mainbody/iliac limbs)*
✓*Bifurcation angulation*

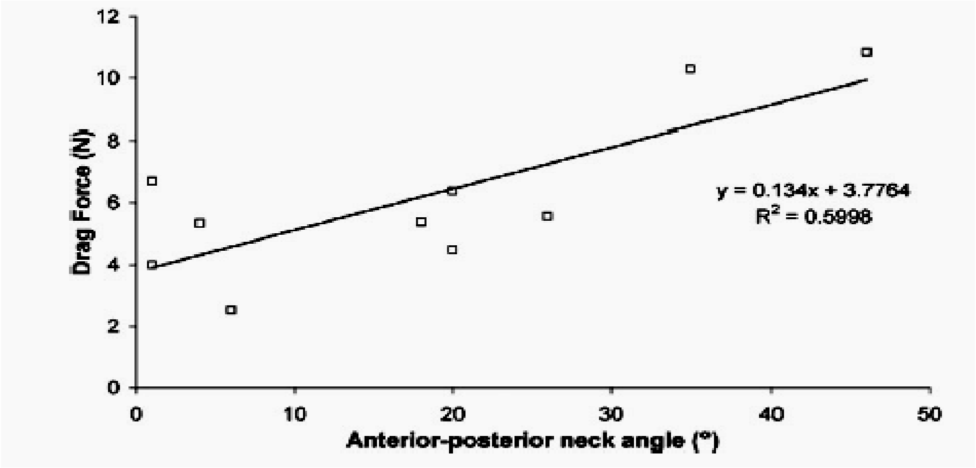


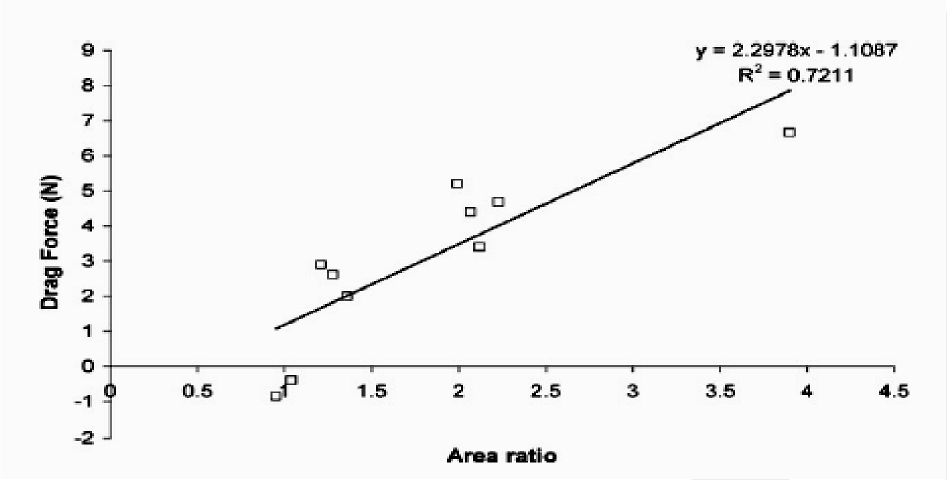


Geometric factors affecting displacement forces on endografts



A Computational Study of the Magnitude and Direction of Migration Forces in Patient-specific Abdominal Aortic Aneurysm Stent-Grafts



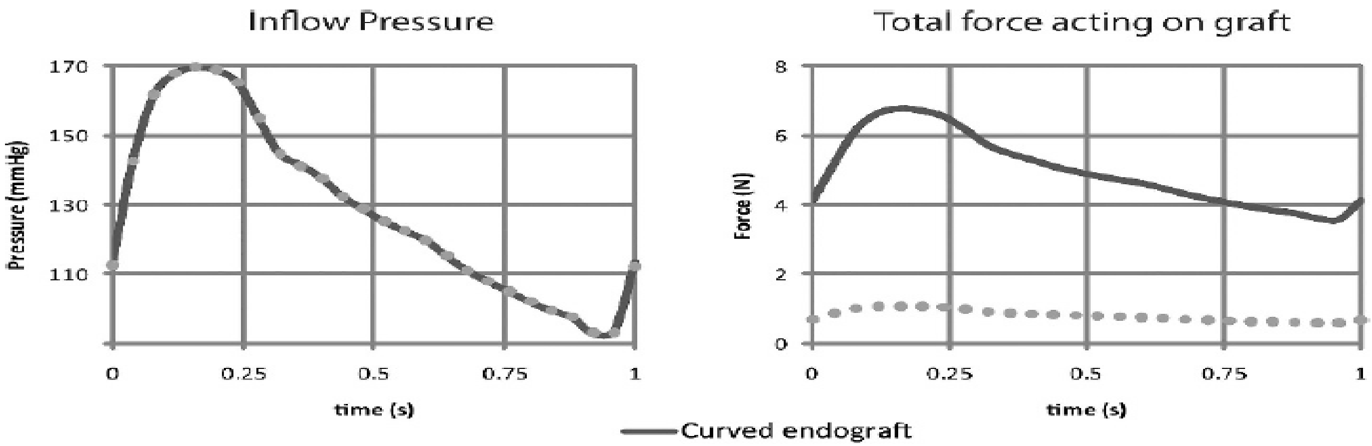


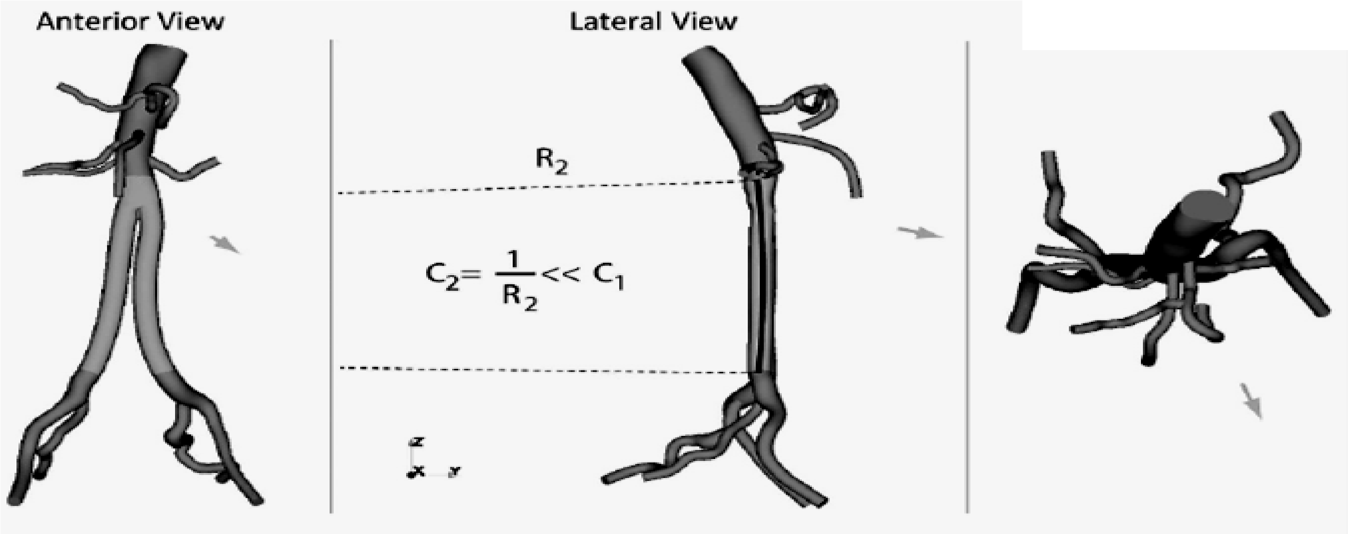
According to Molony et al. that the anteroposterior angle of the neck and the high diameter ratio of inlet/outlet are the most significant parameters to affect the displacement forces

Molony et al, EJVES, 2010; 40:332-9

Geometric factors affecting displacement forces on endografts: curvature

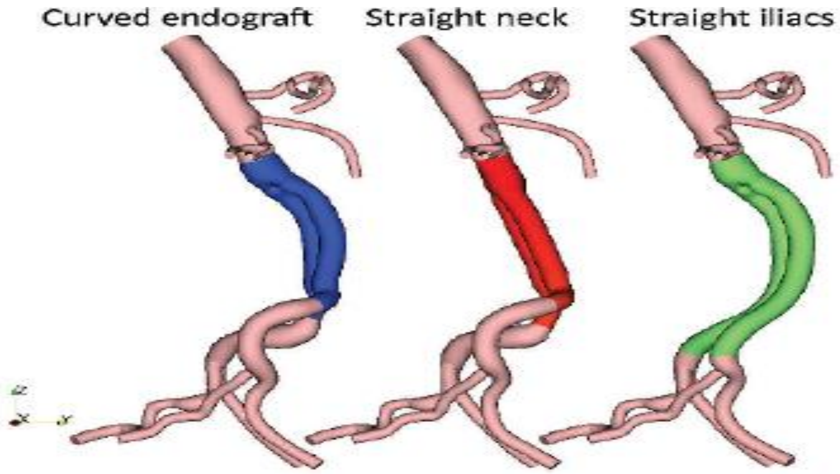
The curvature of endografts increases the displacement forces predisposing to migration

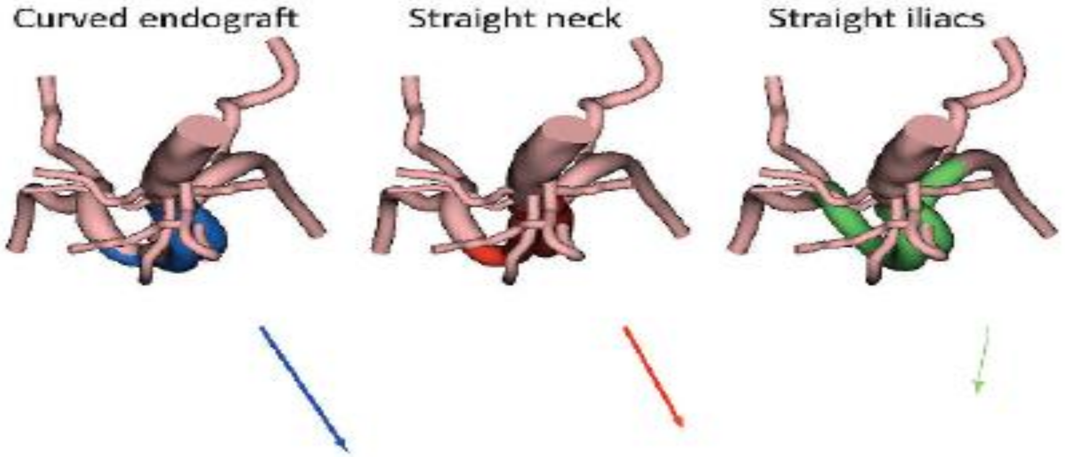




Figueroa et al, EJVES, 2009; 16:284-94

Geometric factors affecting displacement forces: effect of neck & iliac angulation





A straight neck and/or straight iliacs is associated with decreased displacement forces

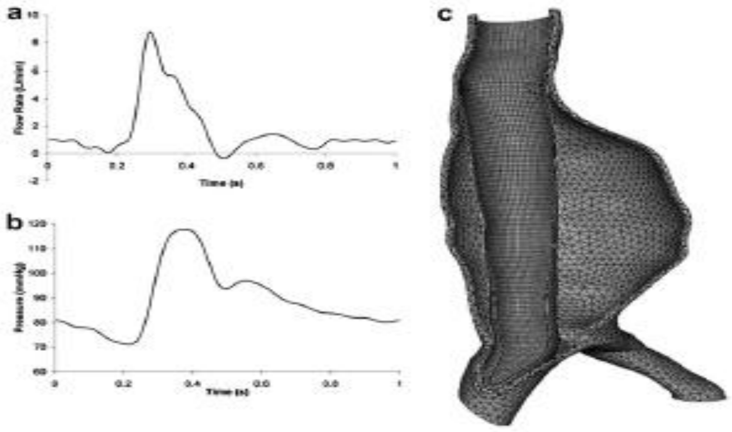
The configuration of neck/iliacs modifies also the direction of displacement forces

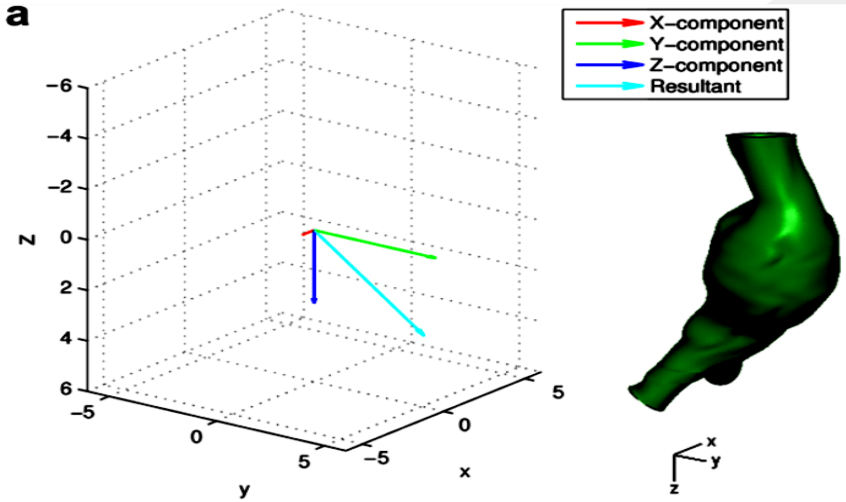
TABLE 2
Total and 3D Components of Displacement Force (F) for the Curved Endograft, Straight Neck, and Straight Iliac Arteries Simulations

	Curved Endograft		Straight Neck		Straight Iliacs
Fx (lateral), N	−2.22		−1.48		0.28
Fy (anterior), N	4.26	>	3.43	>	2.09
Fz (axial), N	−1.42		−1.87		−0.19
Total force, N	5.01		4.18		2.12
% downward	28.35		44.76		8.97

Figueroa et al, EJVES, 2009; 16:284-94

Computational estimation of the direction of displacement forces





The direction of forces: more anterolateral than vertical

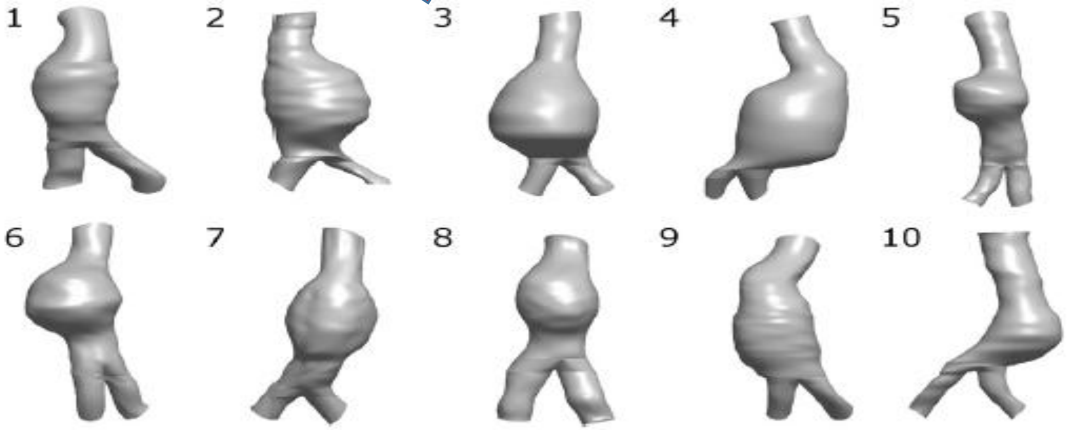
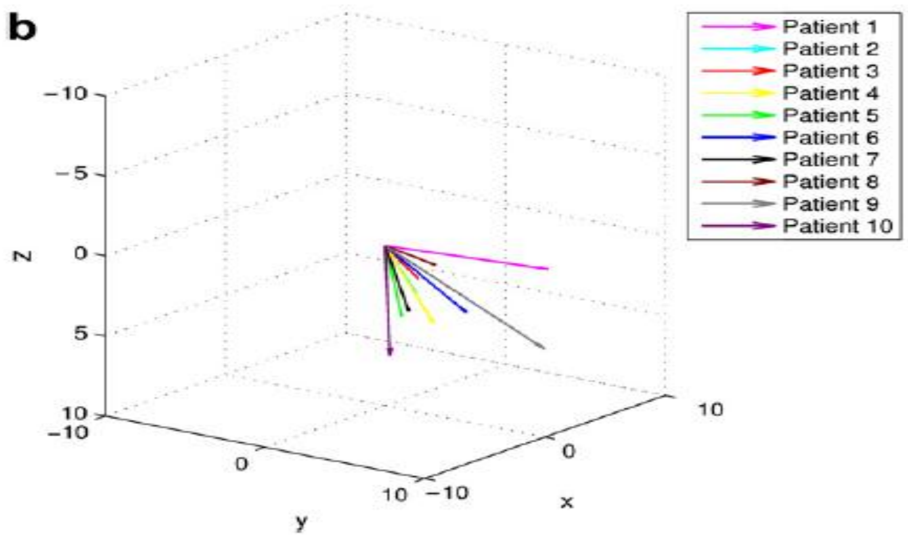


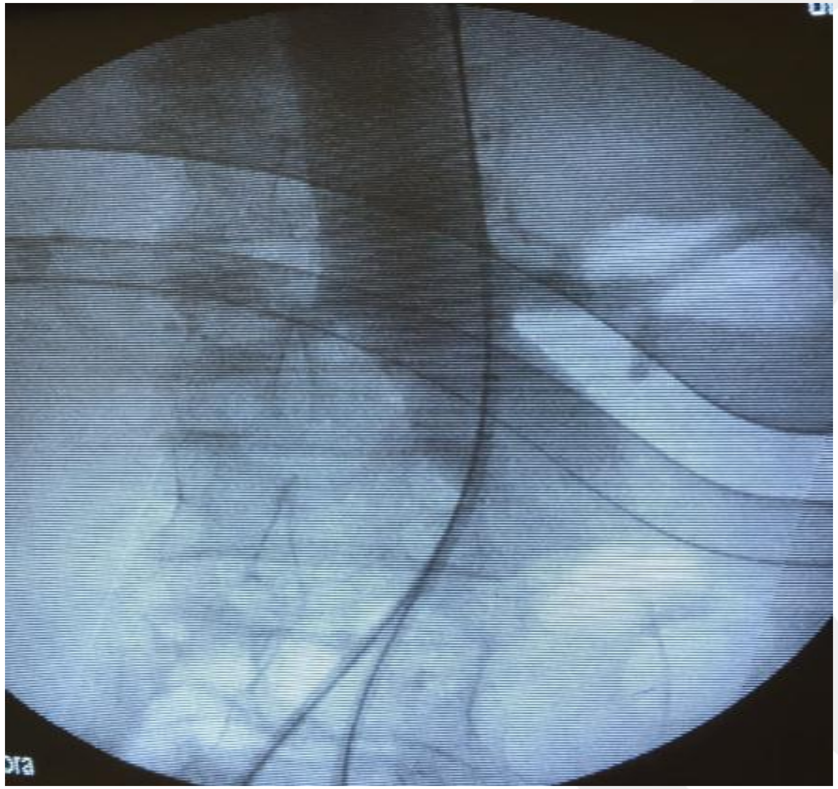
Figure 1 Aneurysm geometry from all 10 patients.



Molony et al, EJVES, 2010; 40:332-9

Curvature of endografts as factor for early complications: a practical example

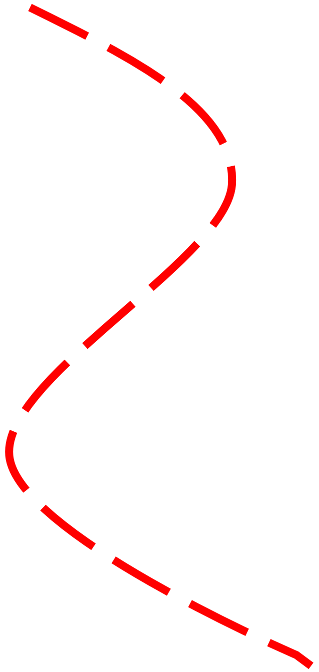
AAA geometry	Patient
Age	54
Comorbidities	CHF, MR
AAA diameter (mm)	61
Neck diameter (mm)	27
Neck morphology	cylindiral
Neck length (mm)	28
Neck angulation	severe
Right CIA length (mm)	65
Right CIA diameter (mm)	33
left CIA length (mm)	70
left CIA diameter (mm)	34
Iliac angulation	severe
CIA aneurysm	bilateral
Fixation to EIA	bilateral
e-tegra size	32x100mm
complications	endoleak Ia
2ndary interventions	Aortic cuff
FU (12m)- outcome	Complete sealing - alive

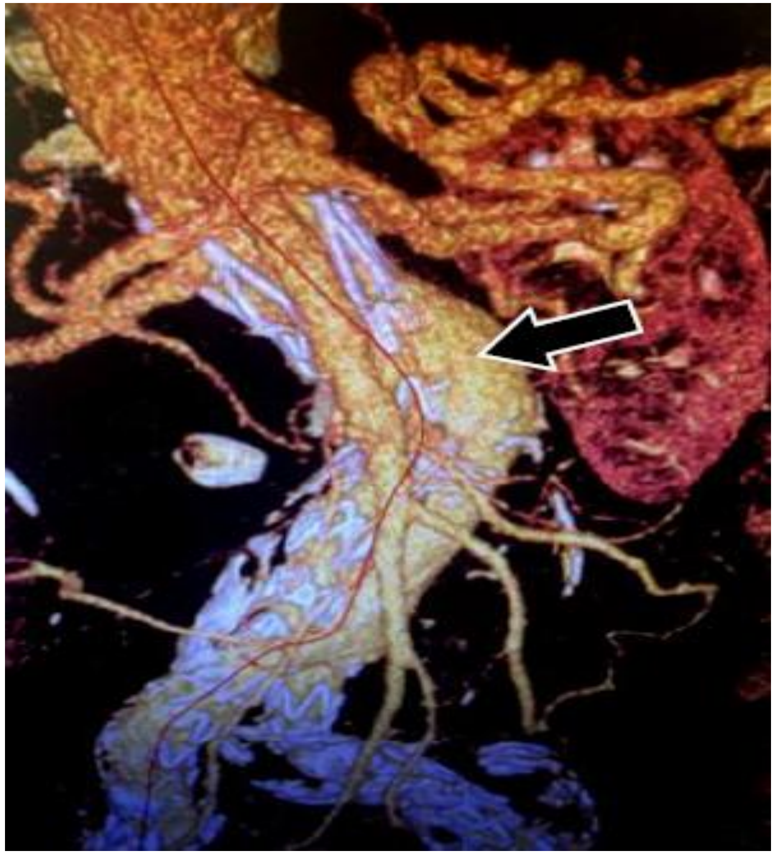


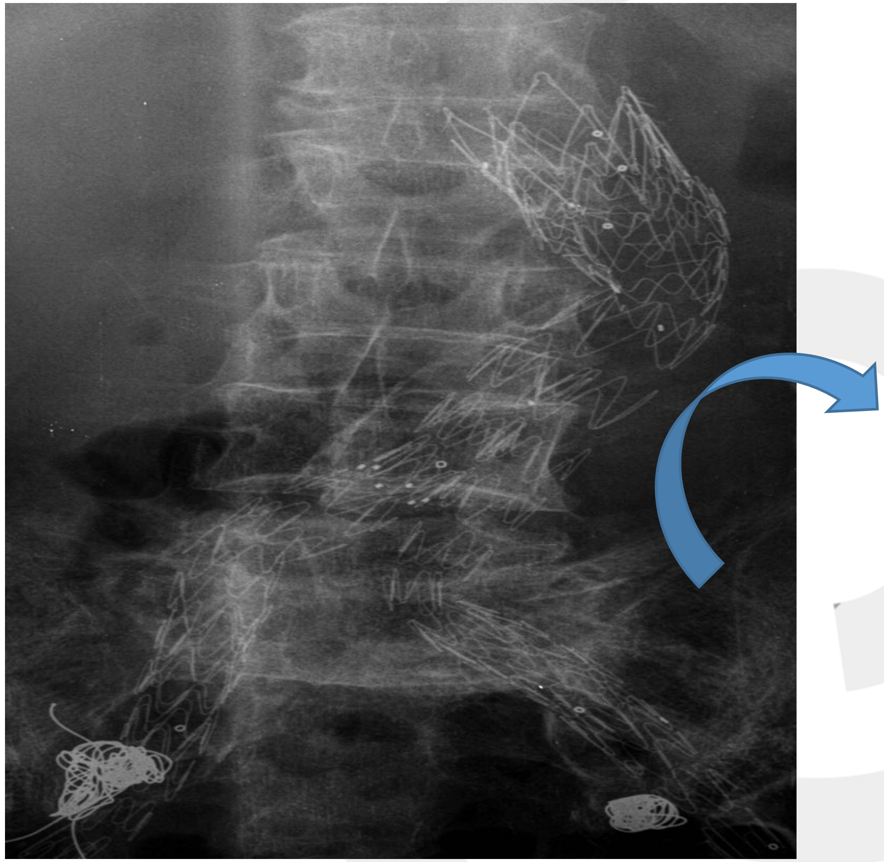
Ideal dimensions of infarenal neck
Introduction of mainbody from the left side…

Curvature of endografts as factor for early complications: a practical example

Endograft curvature/tortuosity



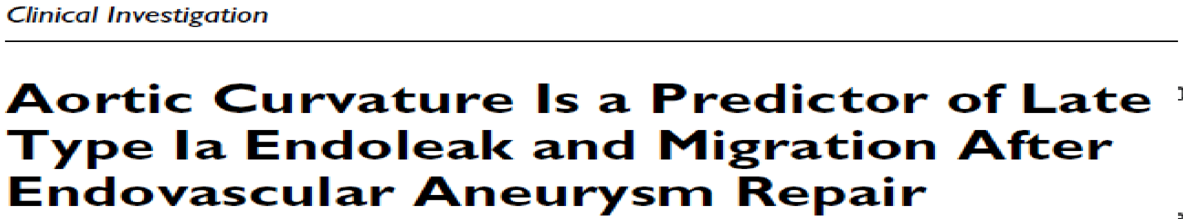




Despite the relative aortic straightening from the Landerquist wires which facillitated endograft deployment, withdrawal of the superstiff wires restored the high curvature and led to immediate migration of the endograft from the site of deployment…this was managed with deployment of an aortic cuff centrally!

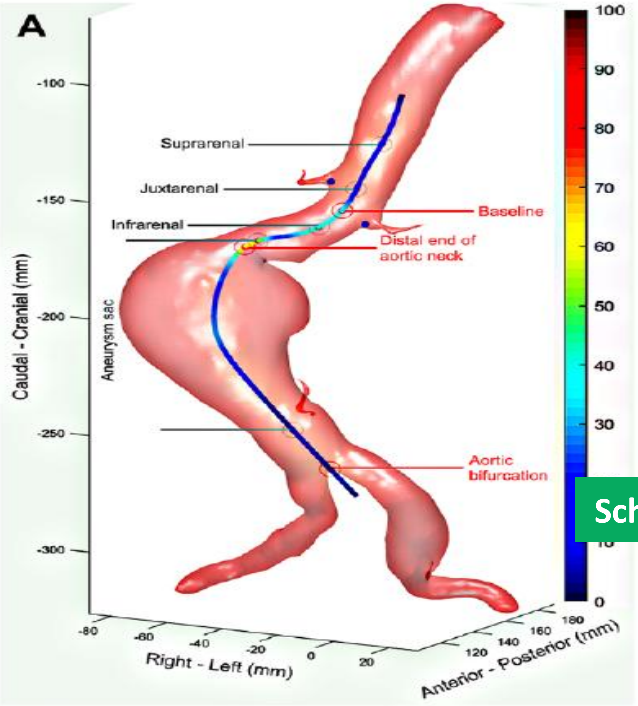
Curvature of endografts as factor for late complications also!

The aforenentioned association of increased displacement forces with excessive endograft curvature explains this phenomenon!

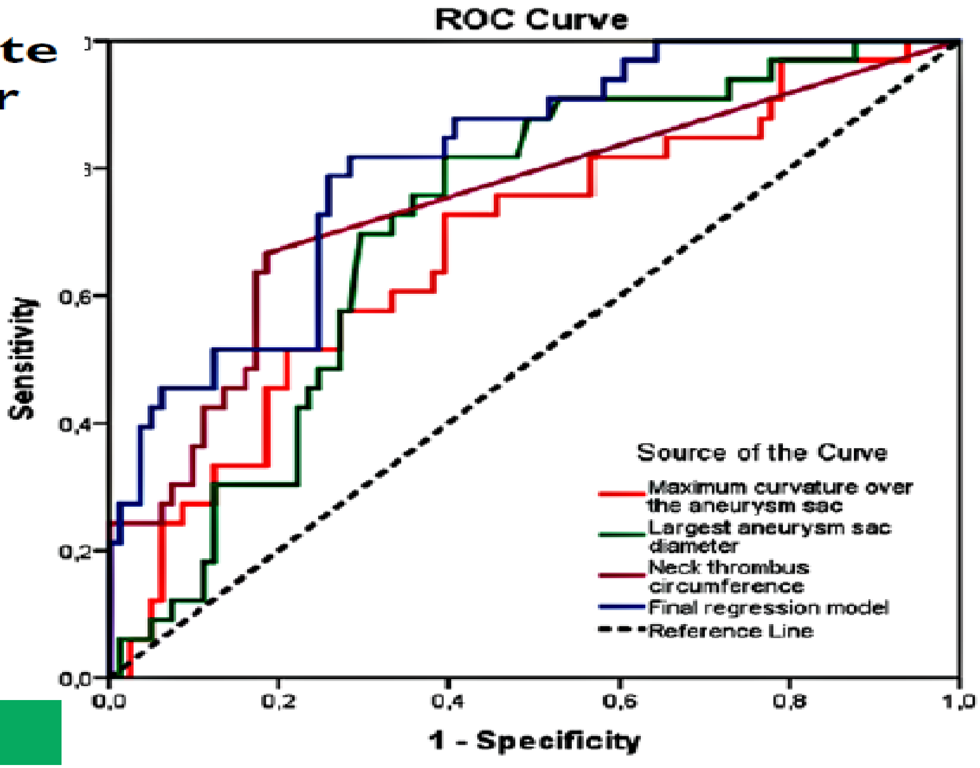


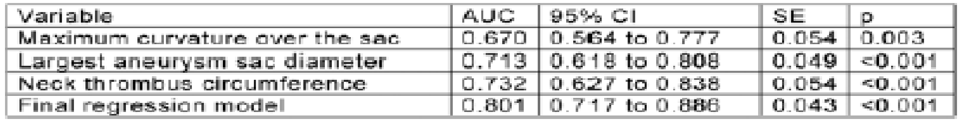
Clinical Investigation

Aortic Curvature Is a Predictor of Late Type Ia Endoleak and Migration After Endovascular Aneurysm Repair



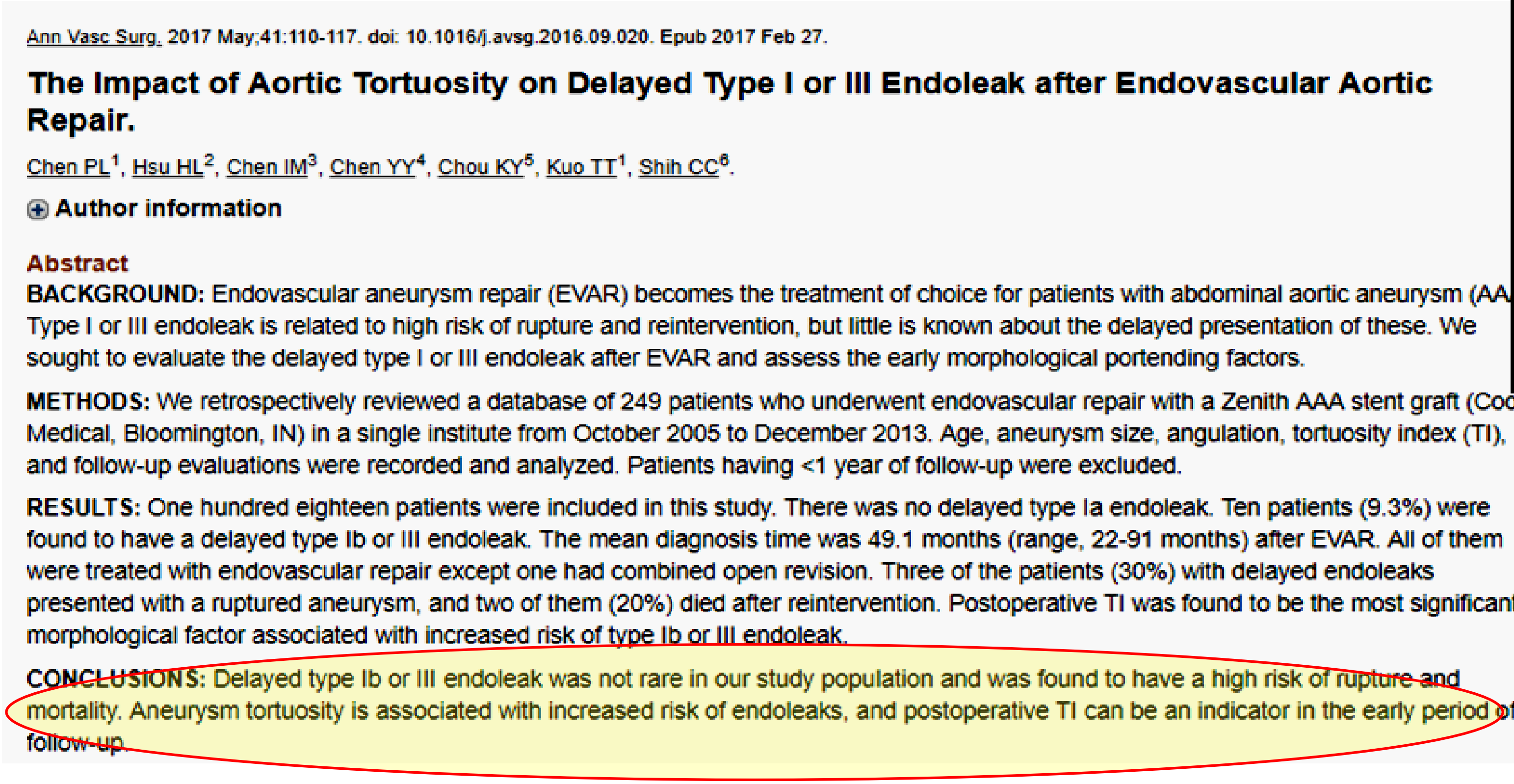
Schuurmann et al, JEVT, 2017 24:411-417





Variable	AUC	95% CI	SE	p
Maximum curvature over the sac	0.670	0.564 to 0.777	0.054	0.003
Largest aneurysm sac diameter	0.713	0.618 to 0.808	0.049	<0.001
Neck thrombus circumference	0.732	0.627 to 0.838	0.054	<0.001
Final regression model	0.801	0.717 to 0.886	0.043	<0.001

Curvature of endografts as factor for late complications also!



Ann Vasc Surg. 2017 May;41:110-117. doi: 10.1016/j.avsg.2016.09.020. Epub 2017 Feb 27.

The Impact of Aortic Tortuosity on Delayed Type I or III Endoleak after Endovascular Aortic Repair.

Chen PL[1], Hsu HL[2], Chen IM[3], Chen YY[4], Chou KY[5], Kuo TT[1], Shih CC[6].

⊕ Author information

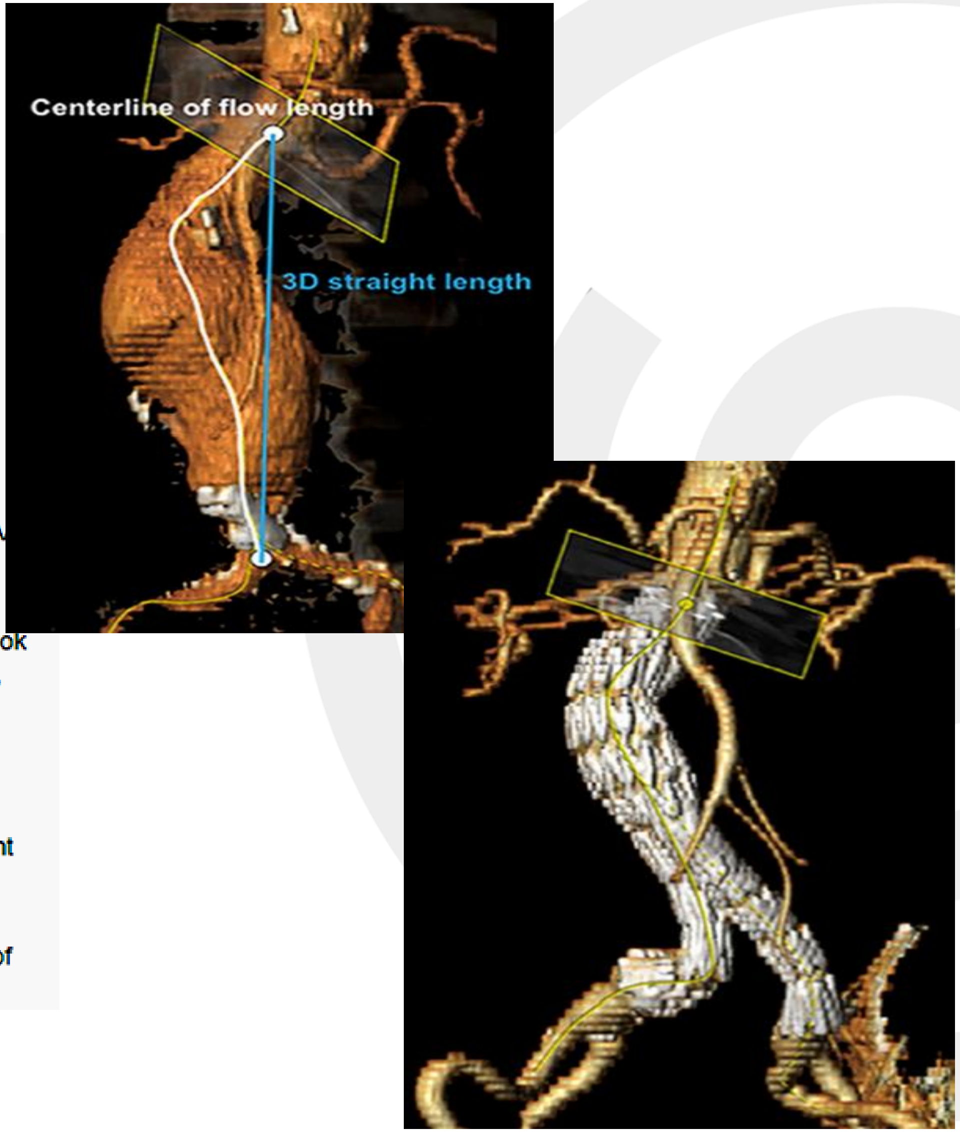
Abstract

BACKGROUND: Endovascular aneurysm repair (EVAR) becomes the treatment of choice for patients with abdominal aortic aneurysm (AA Type I or III endoleak is related to high risk of rupture and reintervention, but little is known about the delayed presentation of these. We sought to evaluate the delayed type I or III endoleak after EVAR and assess the early morphological portending factors.

METHODS: We retrospectively reviewed a database of 249 patients who underwent endovascular repair with a Zenith AAA stent graft (Cook Medical, Bloomington, IN) in a single institute from October 2005 to December 2013. Age, aneurysm size, angulation, tortuosity index (TI), and follow-up evaluations were recorded and analyzed. Patients having <1 year of follow-up were excluded.

RESULTS: One hundred eighteen patients were included in this study. There was no delayed type Ia endoleak. Ten patients (9.3%) were found to have a delayed type Ib or III endoleak. The mean diagnosis time was 49.1 months (range, 22-91 months) after EVAR. All of them were treated with endovascular repair except one had combined open revision. Three of the patients (30%) with delayed endoleaks presented with a ruptured aneurysm, and two of them (20%) died after reintervention. Postoperative TI was found to be the most significant morphological factor associated with increased risk of type Ib or III endoleak.

CONCLUSIONS: Delayed type Ib or III endoleak was not rare in our study population and was found to have a high risk of rupture and mortality. Aneurysm tortuosity is associated with increased risk of endoleaks, and postoperative TI can be an indicator in the early period of follow-up.



Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

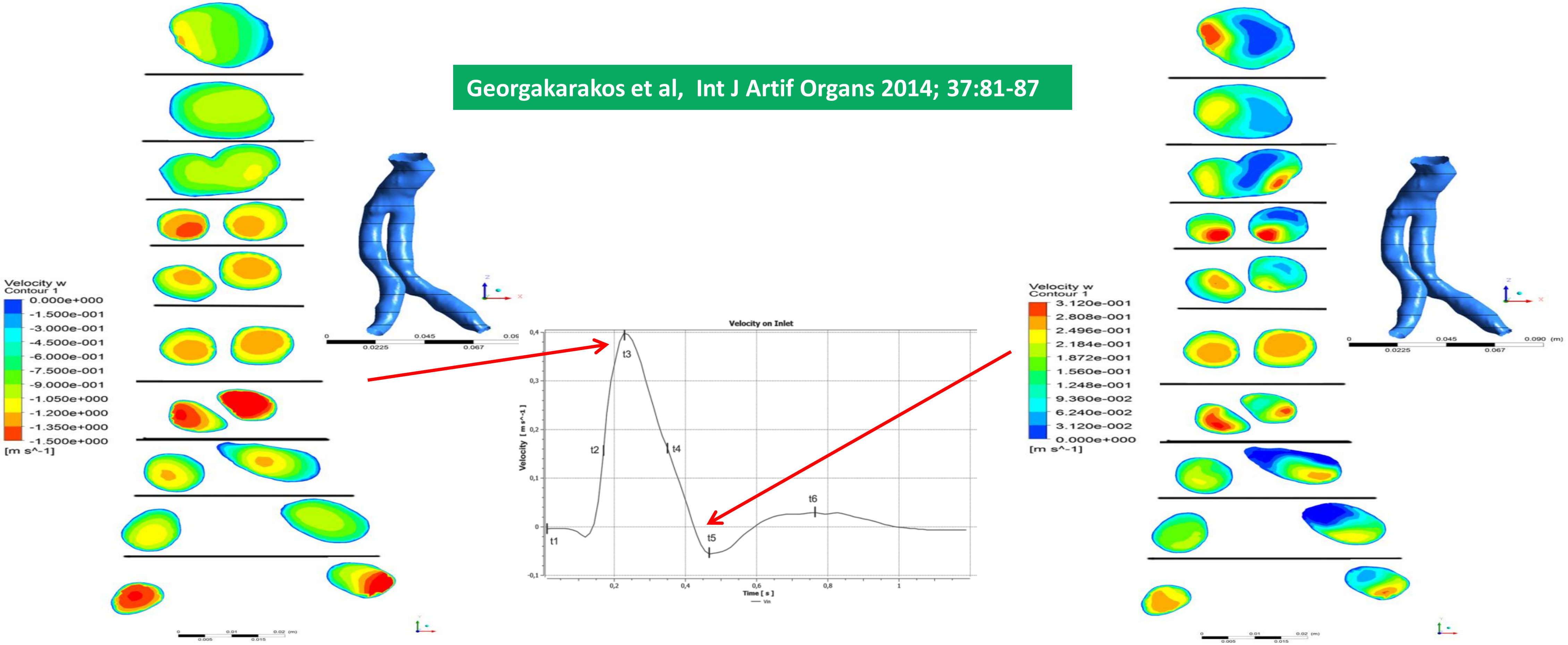
PERFORMANCE OF ENDOGRAFTS

ILIAC LIMBS

- ✓Flow phenomena
- ✓Shear stresses
- ✓Modes of complications

Effect of iliac geometry on flow dynamics

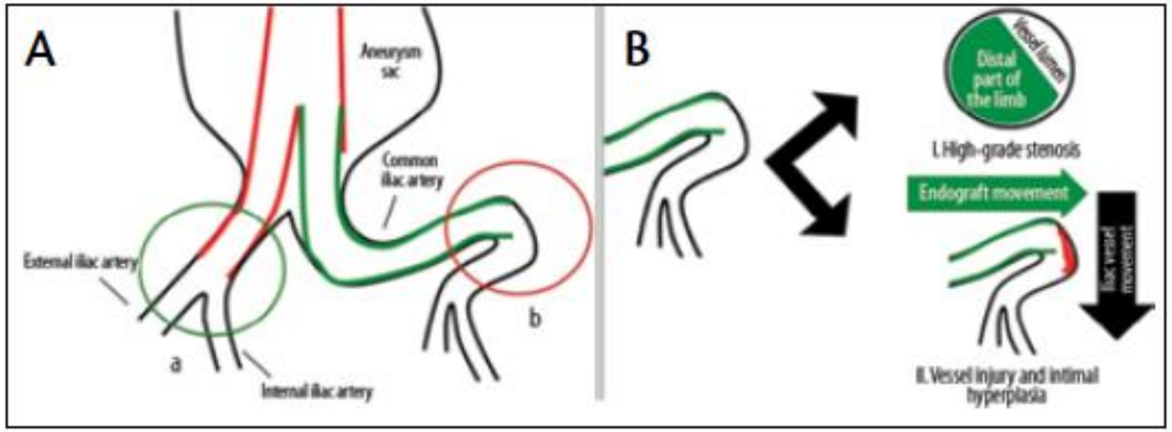
Georgakarakos et al, Int J Artif Organs 2014; 37:81-87

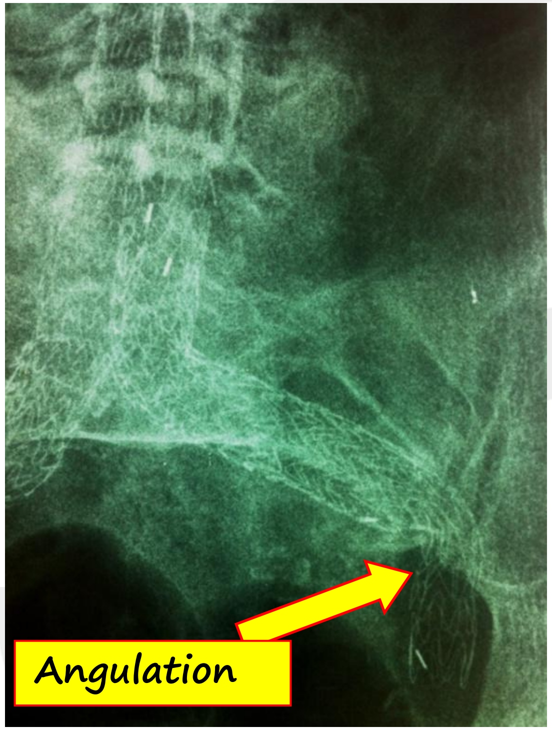


Limbs geometry affects the profile of flow velocity and shear stresses at the limbs…

VASCUPEDIA

Effect of iliac geometry on flow dynamics



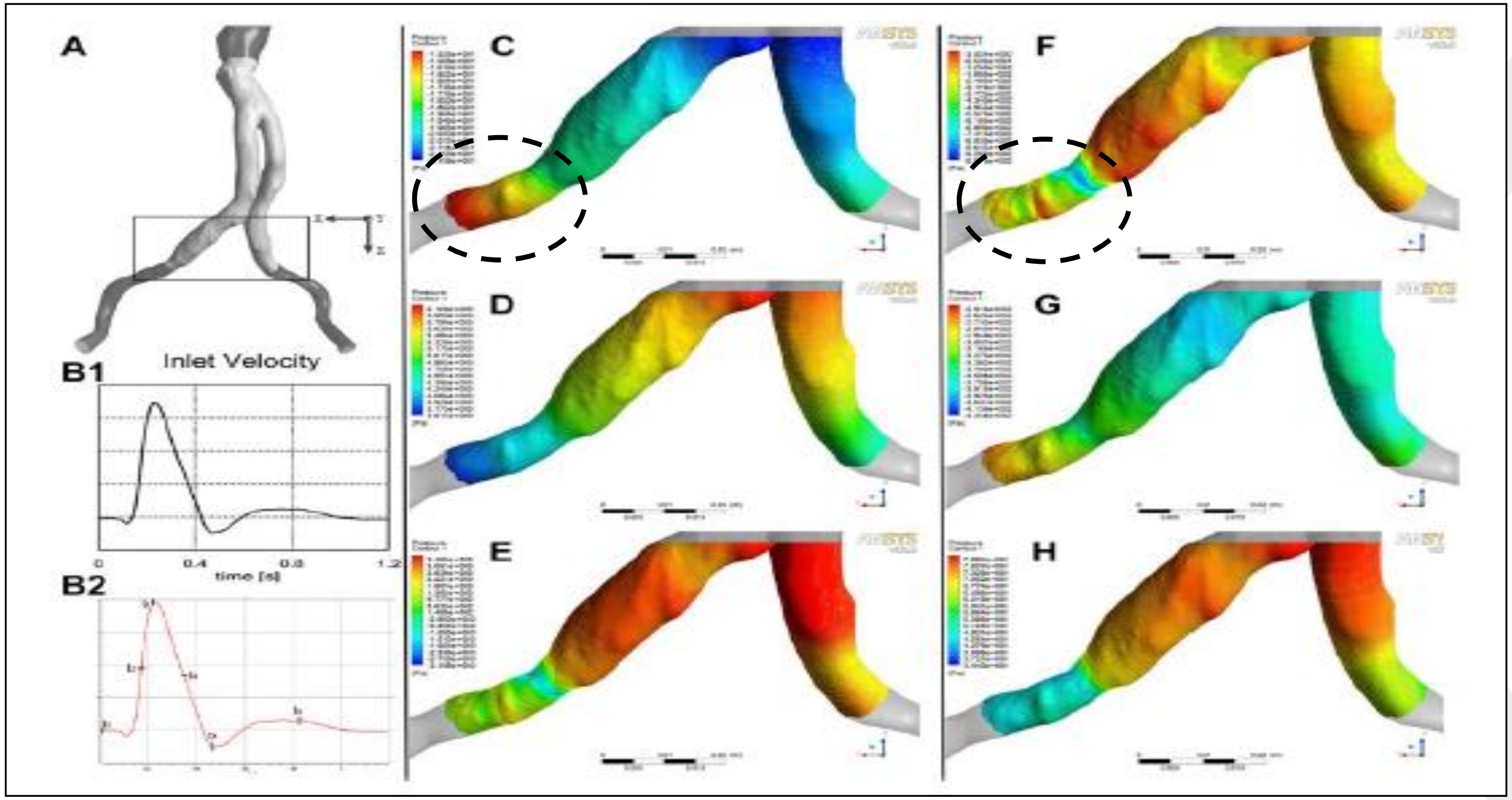


The Influence of iliac tortuosity: suggested mechanism

Suboptimal apposition of the distal end of iliac stent on a curved vessel leads to endothelial injury due to different directions of endograft and artery movement during the cardial cycle → Myointimal hyperplasia → Stenosis → Occlusion

Georgakarakos et al, JEVT, 2017; 22:413-420

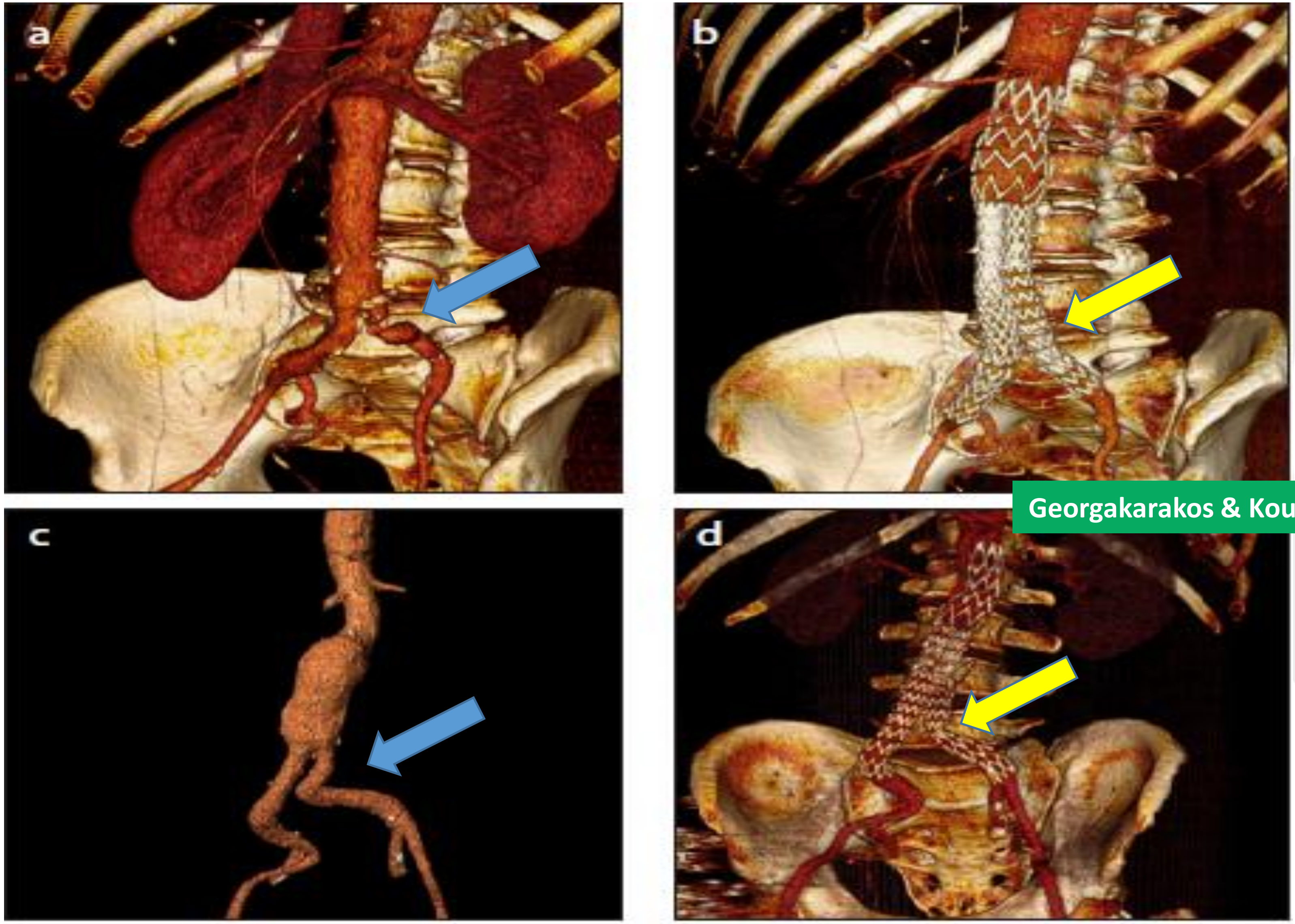
Effect of iliac geometry on flow dynamics



Iliac limb stenosis causes alterations in the distribution of shear stresses and pressures, predisposing to occlusion!

Georgakarakos et al, JEVT, 2017; 22:413-420

Use of balloon-expandable stents to support stenosed iliac limbs



Georgakarakos & Koutsoumpelis, DIR 2018; 24:113-114

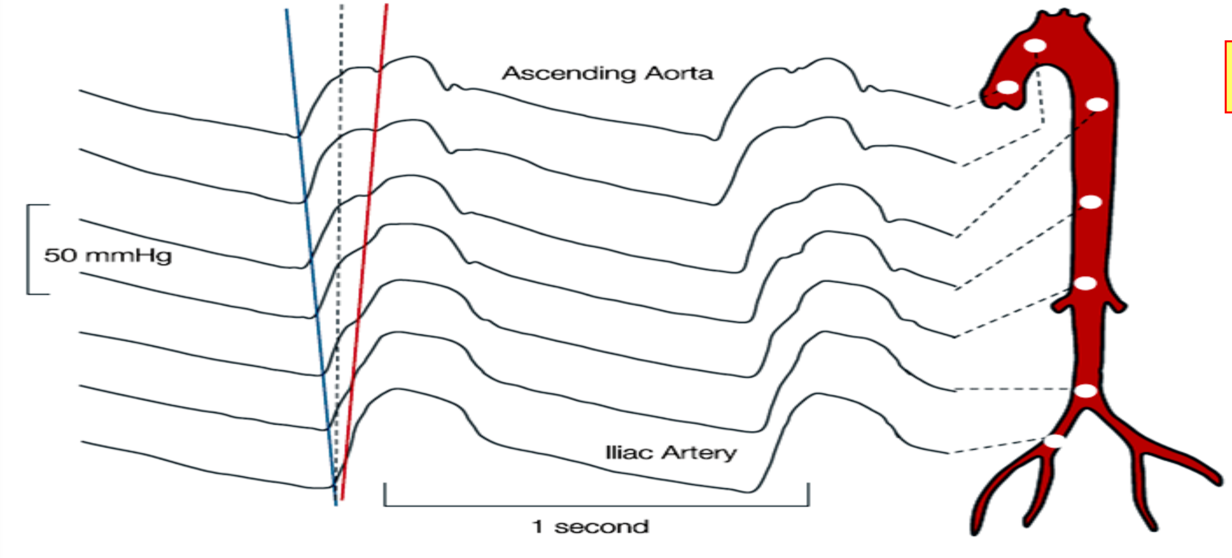
Hemodynamic and mechanical interpretation of the clinical performance of abdominal aortic endografts: principles and considerations

PERFORMANCE OF ENDOGRAFTS

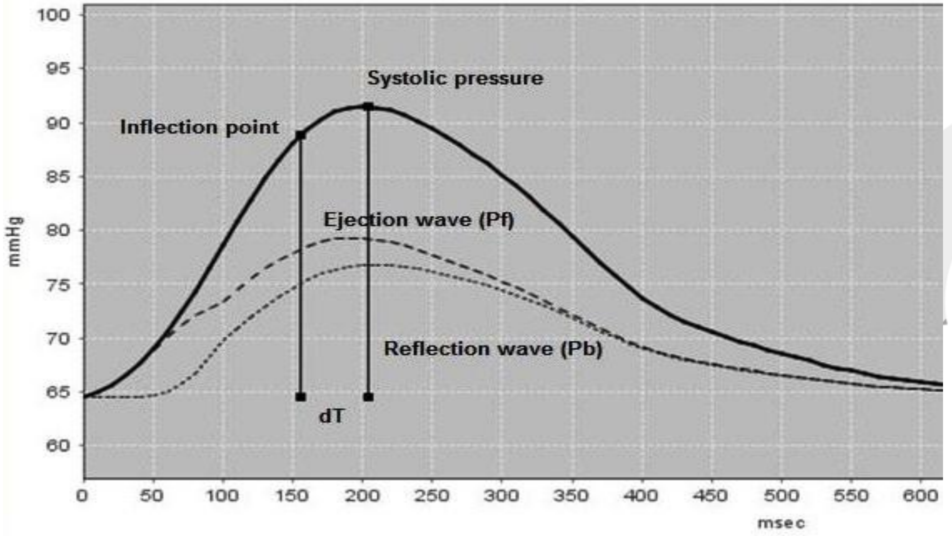
CENTRAL CIRCULATION

- ✓Modes of action
- ✓Mechanical parameters

The effect of endografts on central hemodynamics



How can EVAR affect central hemodynamics ?



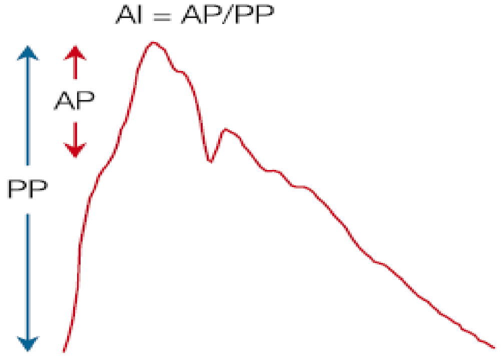
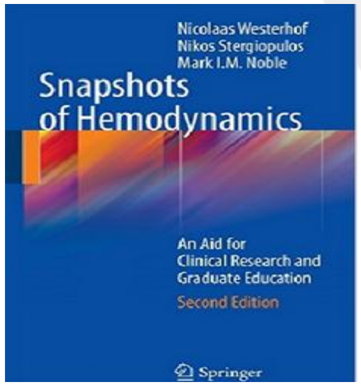


Fig. 21.2 The augmentation index (AI) is the augmented pressure (AP) divided by pulse pressure (PP). Calibration of blood pressure is not required



Nicolaas Westerhof
Nikos Stergiopulos
Mark I.M. Noble

Snapshots of Hemodynamics

An Aid for Clinical Research and Graduate Education

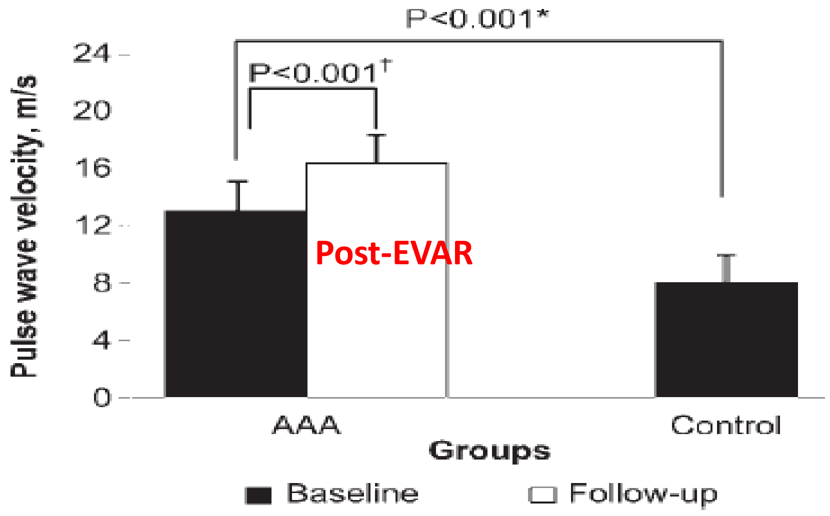
Second Edition

Springer

The effect of endografts on central hemodynamics

Pulse wave velocity increases after EVAR…

J ENDOVASC THER
2012;19;661–666



Changes in pulse wave velocity depend on the type of material and structural designs of endografts

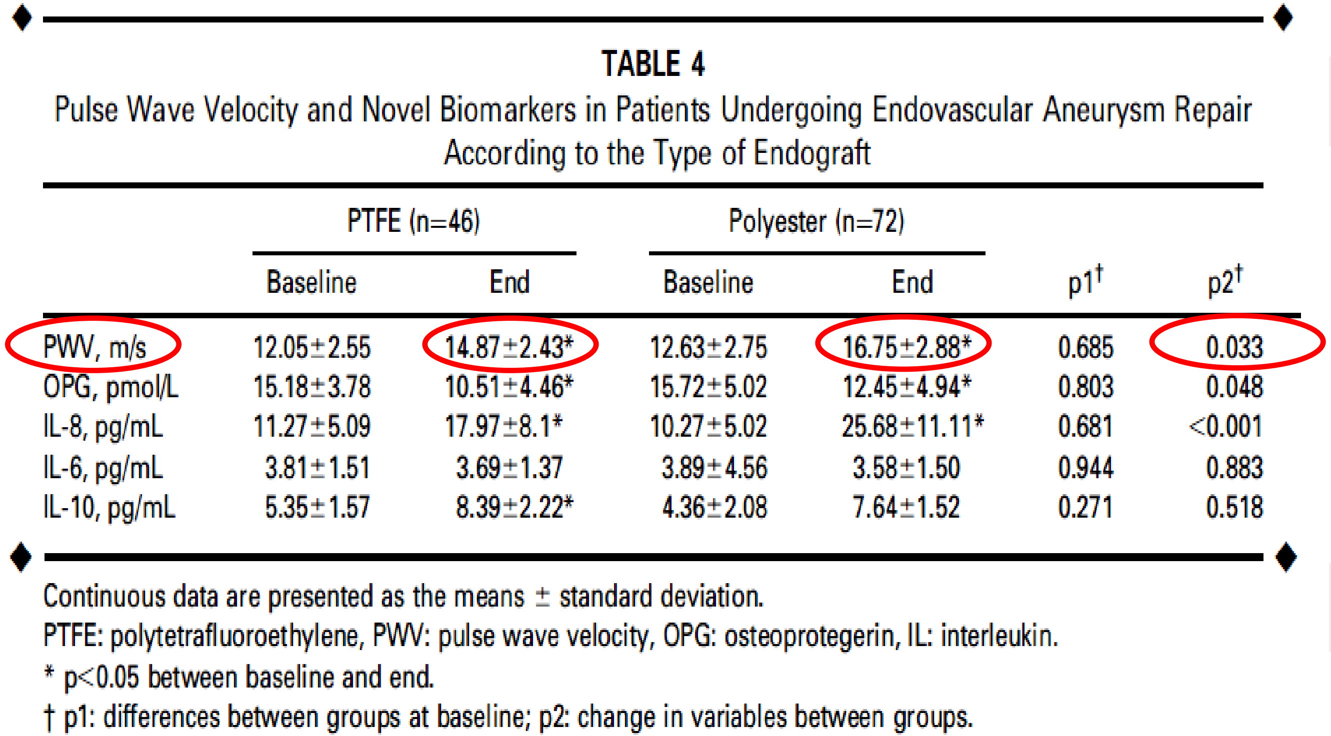


TABLE 4

Pulse Wave Velocity and Novel Biomarkers in Patients Undergoing Endovascular Aneurysm Repair According to the Type of Endograft

	PTFE (n=46)		Polyester (n=72)			
	Baseline	End	Baseline	End	p1†	p2†
PWV, m/s	12.05±2.55	14.87±2.43*	12.63±2.75	16.75±2.88*	0.685	0.033
OPG, pmol/L	15.18±3.78	10.51±4.46*	15.72±5.02	12.45±4.94*	0.803	0.048
IL-8, pg/mL	11.27±5.09	17.97±8.1*	10.27±5.02	25.68±11.11*	0.681	<0.001
IL-6, pg/mL	3.81±1.51	3.69±1.37	3.89±4.56	3.58±1.50	0.944	0.883
IL-10, pg/mL	5.35±1.57	8.39±2.22*	4.36±2.08	7.64±1.52	0.271	0.518

Continuous data are presented as the means ± standard deviation.
PTFE: polytetrafluoroethylene, PWV: pulse wave velocity, OPG: osteoprotegerin, IL: interleukin.
* p<0.05 between baseline and end.
† p1: differences between groups at baseline; p2: change in variables between groups.

J ENDOVASC THER
2014;21:850–858

The effect of endografts on central hemodynamics

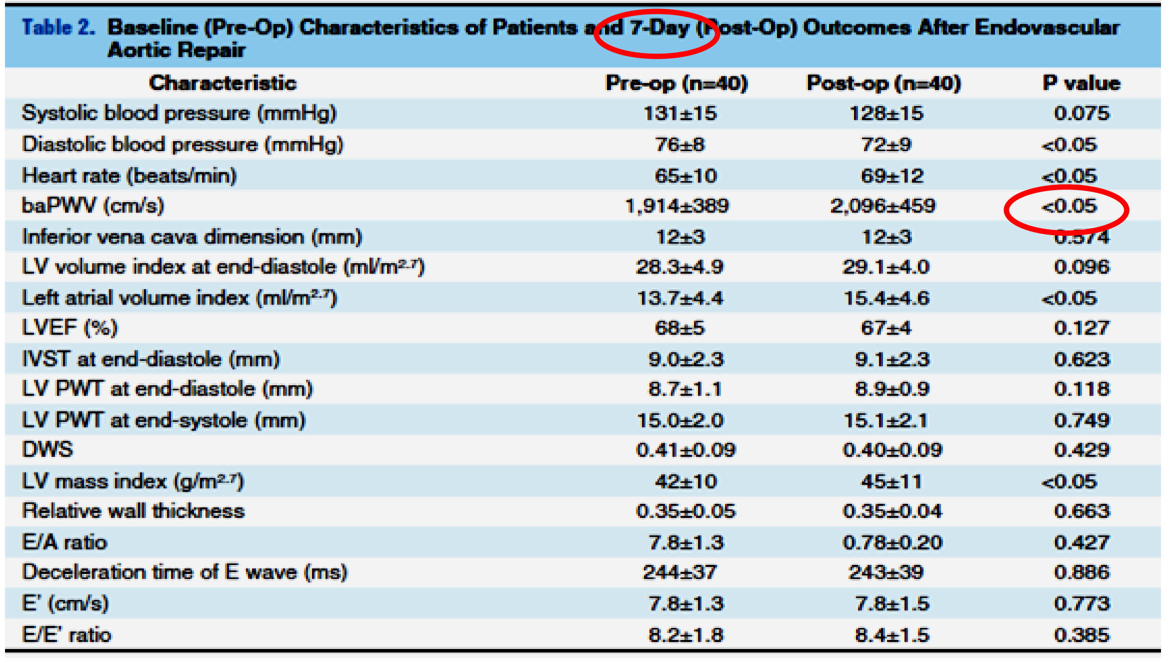


Table 2. Baseline (Pre-Op) Characteristics of Patients and 7-Day (Post-Op) Outcomes After Endovascular Aortic Repair

Characteristic	Pre-op (n=40)	Post-op (n=40)	P value
Systolic blood pressure (mmHg)	131±15	128±15	0.075
Diastolic blood pressure (mmHg)	76±8	72±9	<0.05
Heart rate (beats/min)	65±10	69±12	<0.05
baPWV (cm/s)	1,914±389	2,096±459	<0.05
Inferior vena cava dimension (mm)	12±3	12±3	0.574
LV volume index at end-diastole (ml/m$^{2.7}$)	28.3±4.9	29.1±4.0	0.096
Left atrial volume index (ml/m$^{2.7}$)	13.7±4.4	15.4±4.6	<0.05
LVEF (%)	68±5	67±4	0.127
IVST at end-diastole (mm)	9.0±2.3	9.1±2.3	0.623
LV PWT at end-diastole (mm)	8.7±1.1	8.9±0.9	0.118
LV PWT at end-systole (mm)	15.0±2.0	15.1±2.1	0.749
DWS	0.41±0.09	0.40±0.09	0.429
LV mass index (g/m$^{2.7}$)	42±10	45±11	<0.05
Relative wall thickness	0.35±0.05	0.35±0.04	0.663
E/A ratio	7.8±1.3	0.78±0.20	0.427
Deceleration time of E wave (ms)	244±37	243±39	0.886
E' (cm/s)	7.8±1.3	7.8±1.5	0.773
E/E' ratio	8.2±1.8	8.4±1.5	0.385

Takeda et al, Circul J 2014; 78: 322-8

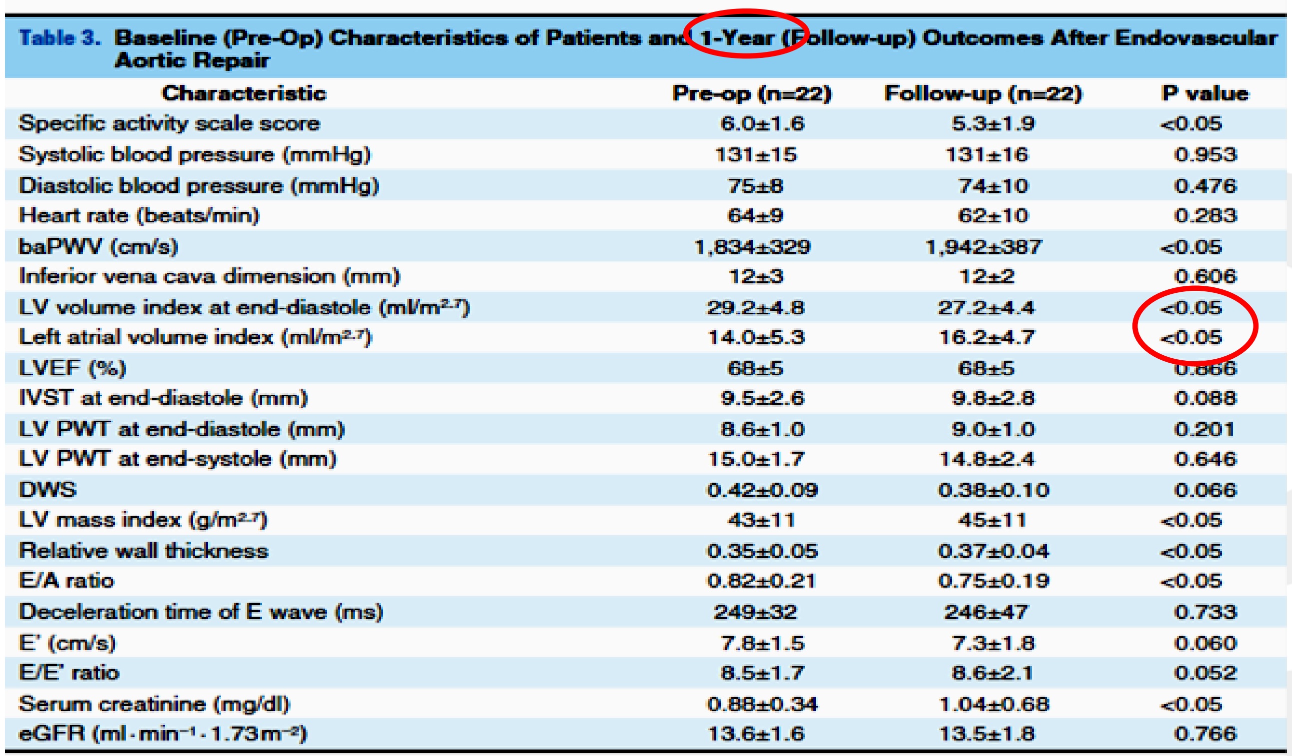


Table 3. Baseline (Pre-Op) Characteristics of Patients and 1-Year (Follow-up) Outcomes After Endovascular Aortic Repair

Characteristic	Pre-op (n=22)	Follow-up (n=22)	P value
Specific activity scale score	6.0±1.6	5.3±1.9	<0.05
Systolic blood pressure (mmHg)	131±15	131±16	0.953
Diastolic blood pressure (mmHg)	75±8	74±10	0.476
Heart rate (beats/min)	64±9	62±10	0.283
baPWV (cm/s)	1,834±329	1,942±387	<0.05
Inferior vena cava dimension (mm)	12±3	12±2	0.606
LV volume index at end-diastole (ml/m$^{2.7}$)	29.2±4.8	27.2±4.4	<0.05
Left atrial volume index (ml/m$^{2.7}$)	14.0±5.3	16.2±4.7	<0.05
LVEF (%)	68±5	68±5	0.866
IVST at end-diastole (mm)	9.5±2.6	9.8±2.8	0.088
LV PWT at end-diastole (mm)	8.6±1.0	9.0±1.0	0.201
LV PWT at end-systole (mm)	15.0±1.7	14.8±2.4	0.646
DWS	0.42±0.09	0.38±0.10	0.066
LV mass index (g/m$^{2.7}$)	43±11	45±11	<0.05
Relative wall thickness	0.35±0.05	0.37±0.04	<0.05
E/A ratio	0.82±0.21	0.75±0.19	<0.05
Deceleration time of E wave (ms)	249±32	246±47	0.733
E' (cm/s)	7.8±1.5	7.3±1.8	0.060
E/E' ratio	8.5±1.7	8.6±2.1	0.052
Serum creatinine (mg/dl)	0.88±0.34	1.04±0.68	<0.05
eGFR (ml·min^{-1}·1.73m^{-2})	13.6±1.6	13.5±1.8	0.766

EVAR affects PWV directly postoperatively (from the 1st week), while it also affects cardiac function (left ventricle volume index at end-diastole and left atrial volume index) in the long-term, i.e., alteration of vascular stiffness, cardiac structure and function!

Take home messages

- ✓ *Stent implantation causes geometric changes that impose flow disturbance and stress alterations on the vessel wall*
- ✓ *Studying combinations of geometrical features has better predictive role that a sole geometric parameter*
- ✓ *No endograft is ideal; rather, every design serves ideally certain AAA anatomies while less efficiently some others*
- ✓ *Forces predisposing to migration and dislodgement of endografts are increased by certain geometrical factors*
- ✓ *The degree of oversizing of endografts' central segments has important implications since it affects the efficiency of apposition and heterogeneity of applied forces*
- ✓ *Iliac tortuosity and endograft's curvature have an intriguing role in the postimplantational stability*
- ✓ *EVAR can increase arterial pulse-wave-velocity with potential late consequences*

Questions to Vascupedians

- *Do you routinely use endografts with suprarenal fixation or reserve them for cases of angulated infrarenal necks?*
- *Would you consider primary distal-end stenting in cases of suboptimal apposition of iliac-limbs on tortuous vessels?*
- *Would you change your EVAR-practice over infarenal necks of marginally large diameter? How often would you consider a Nitinol-free based endograft strategy?*
- *Are you concerned about the potential influence of EVAR on pulse wave velocity and/or myocardial function?*
- *Would you modify your CT follow-up strategy in cases of "risky" geometrical factors predisposing to migration?*
- *Which geometrical parameter(s) would you be most sceptical for?*
- *Are you concerned about migration of iliac limbs & loss of sealing (endoleak Ib) in cases of iliac tortuosity?*
- *What is your usual strategy of proximal oversizing in cases of short or angulated necks?*