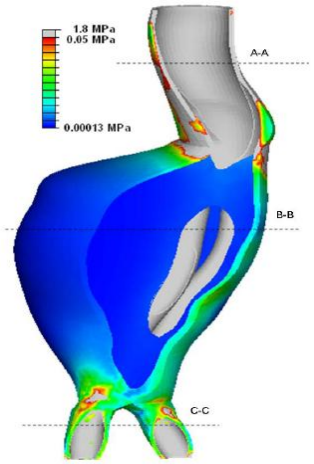
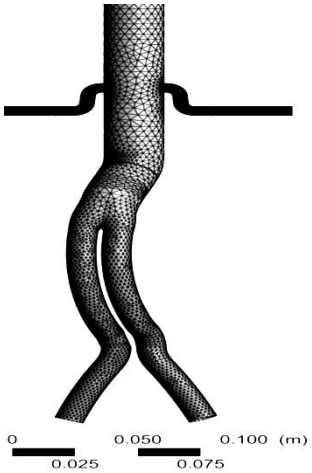
Οργάνωση και Λειτουργία
Αγγειοχειρουργική Κλινική Ιατρικής Σχολής
Πανεπιστημίου Αθηνών Π.Γ.Ν. «Αττικόν»

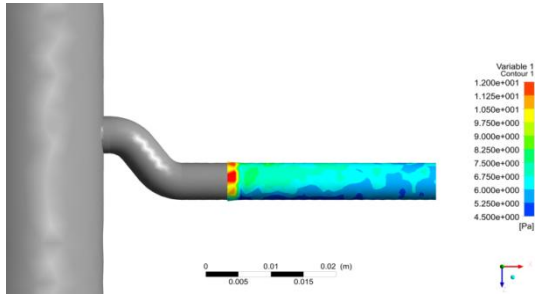
Σε συνεργασία με
Dept. of Surgical Sciences
University of Milano - Bicocca

ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

Αιμοδυναμικές αρχές των ενδοαυλικών μοσχευμάτων
10/09/2022



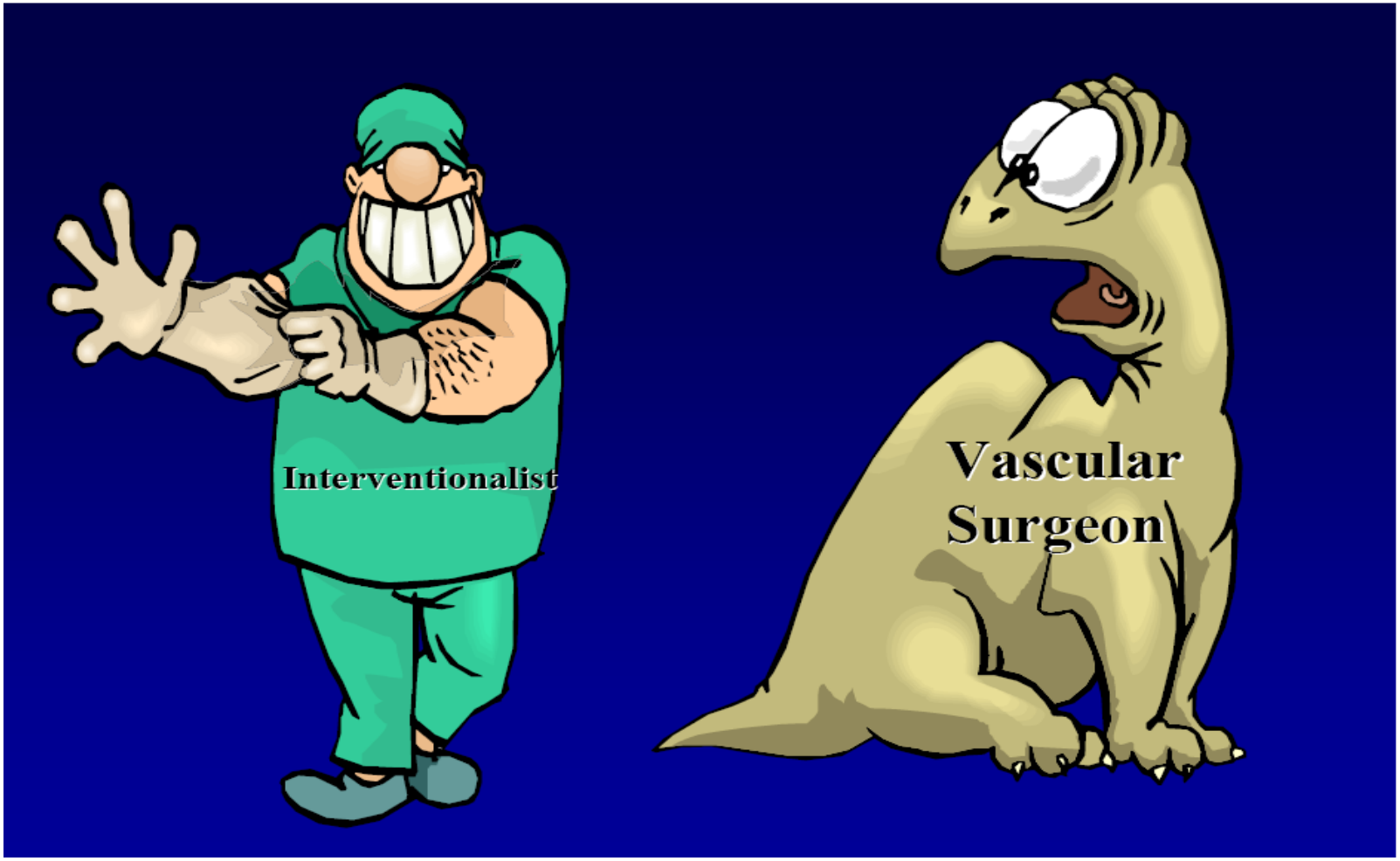




Ευστράτιος Ι. Γεωργακαράκος

Αναπλ. Καθηγητής Αγγειοχειρουργικής
Δημοκρίτειο Πανεπιστήμιο Θράκης

ΑΝΟΙΚΤΗ VS. ΕΝΔΑΓΓΕΙΑΚΗ ΤΕΧΝΙΚΗ

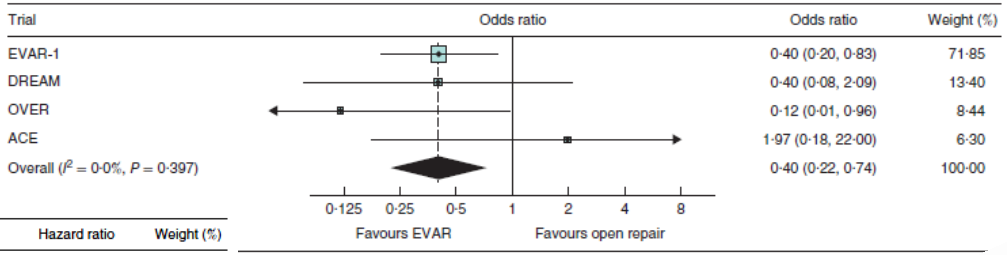


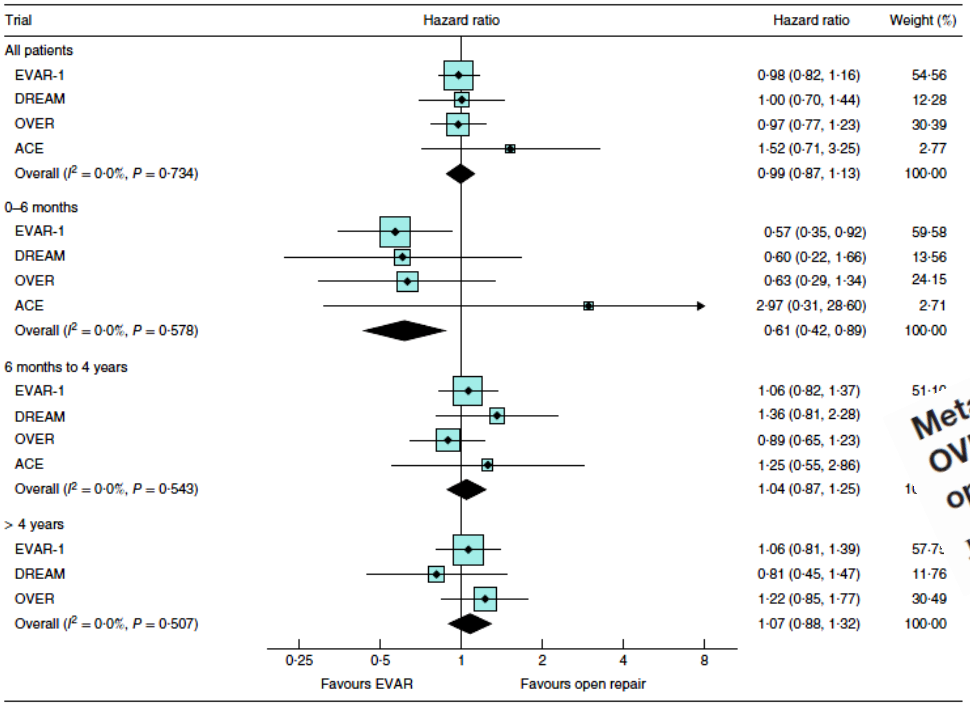
Endovascular versus open repair of abdominal aortic aneurysm in 15-years' follow-up of the UK endovascular aneurysm repair trial 1 (EVAR trial 1): a randomised controlled trial

*Rajesh Patel, Michael J Sweeting, Janet T Powell, Roger M Greenhalgh, for the EVAR trial investigators**

Lancet 2016; 388: 2366–74

Interpretation EVAR has an early survival benefit but an inferior late survival compared with open repair, which needs to be addressed by lifelong surveillance of EVAR and re-intervention if necessary.





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

Απλή υδραυλική; Όχι ακριβώς…

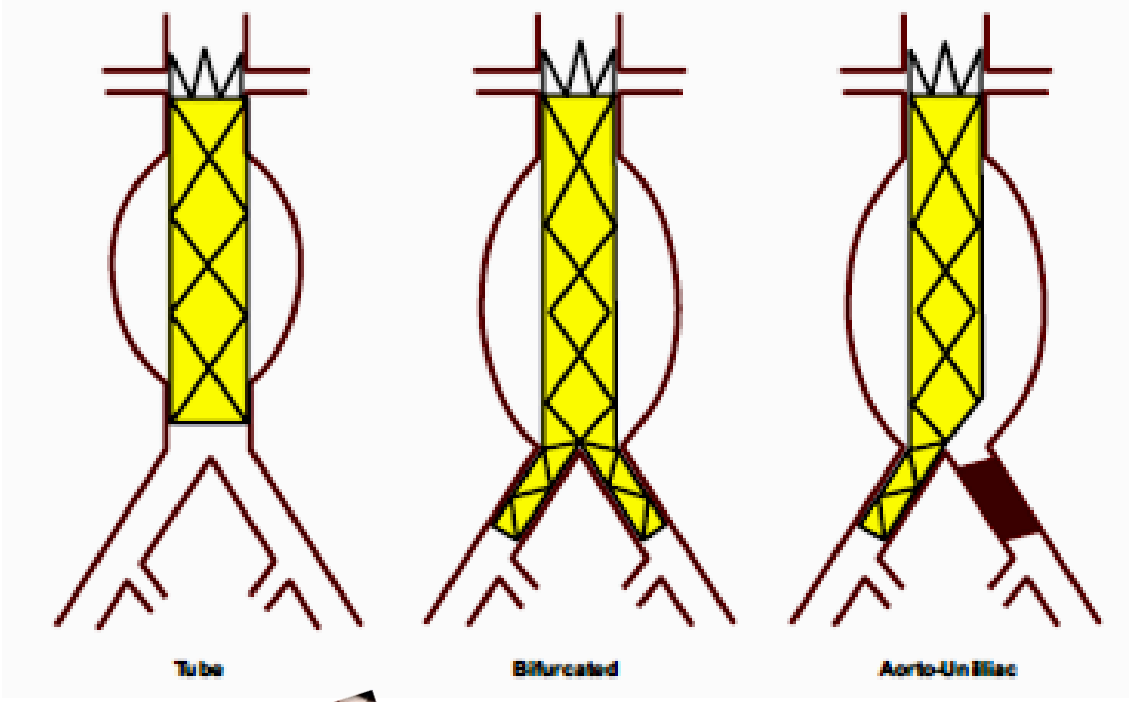
Η βραχυπρόθεσμη, μεσο- & μακροπρόθεσμη συμπεριφορά των ενδομοσχευμάτων εξαρτάται από τις φυσικές και μηχανικές ιδιότητες των μοσχευμάτων και της αορτής (ανευρύσματος)

Eur J Vasc Endovasc Surg (2019) 58, 477–478

EDITORIAL

Effects of Aortic Graft Implantation on Heart and Downstream Vessels: An Artery is not a Rigid Pipe

ΔΙΑΜΟΡΦΩΣΕΙΣ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ



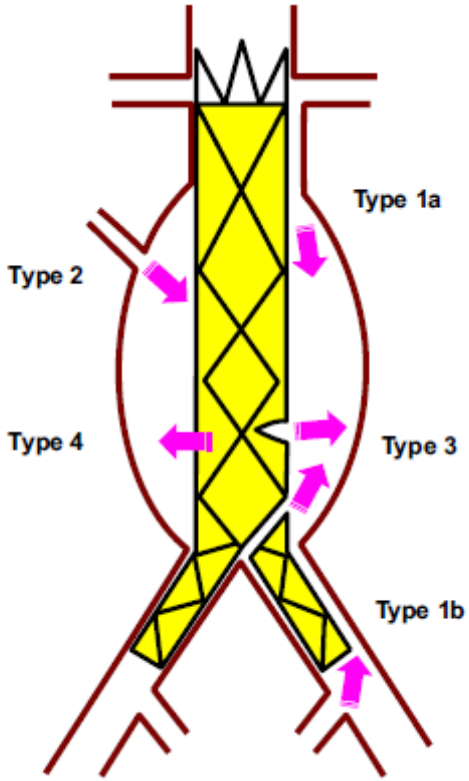


FIGURE 38.2 Types of endoleaks.

ΤΥΠΟΙ ΕΝΔΟΔΙΑΦΥΓΩΝ

Radiol med (2017) 122:309–318
DOI 10.1007/s11547-017-0724-z

VASCULAR AND INTERVENTIONAL RADIOLOGY

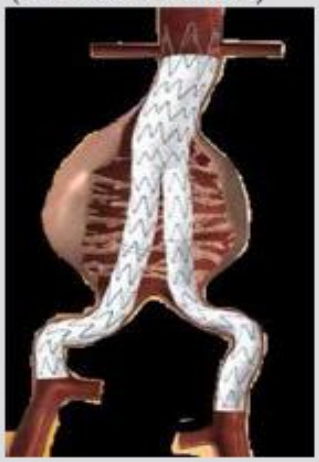
A critical appraisal of endovascular stent-grafts in the management of abdominal aortic aneurysms

Nikolaos Schoretsanitis[1] · Efstratios Georgakarakos[1] · Christos Argyriou[1] · Kiriakos Ktenidis[2] · George S. Georgiadis[1]

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

Endurant II
(Medtronic)



Excluder
(Gore)

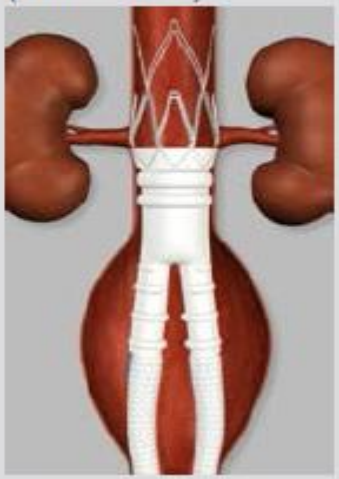
Zenith Flex
(Cook Medical)

Incraft
(Cordis)

AFX
(Endologix)

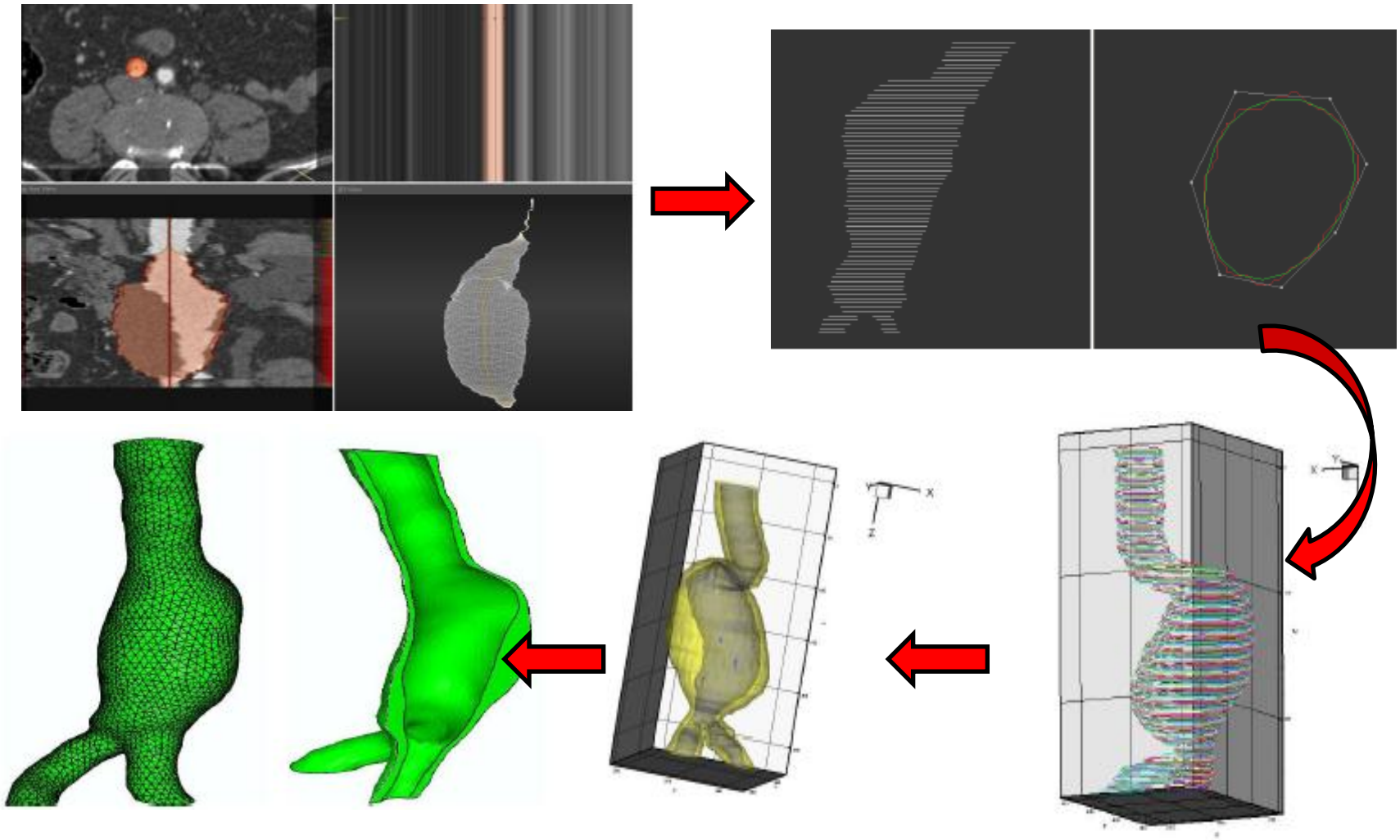
Aorfix
(Lombard)

Ovation
(Trivascular)



Nellix
(Endologix)

Βασικά στάδια της υπολογιστικής προσομοίωσης



Georgakarakos E.I., PhD Thesis, University of Crete, 2009

Table 1. Geometric characteristics of the abdominal aortic aneurysm (AAA) reconstructed 3D model.

Aneurysm model	
Inlet diameter (R1)	24 mm
Iliac outlet diameter (R2)	12 mm
Renal outlet diameter (R3)	6 mm
Aneurysm diameter (R4)	70 mm
Aneurysm length (L1)	190 mm

The dimensions above are depicted in Fig. 1B.

Table 2. Geometric characteristics of the endograft (EG) reconstructed 3D model.

Aneurysm model	
Inlet diameter (R1)	24 mm
Iliac outlet diameter (R2)	12 mm
Renal outlet diameter (R3)	6 mm
Inlet segment length (L2)	110 mm
Iliac segment length (L3)	150 mm
Renal segment length (L4)	30 mm
Curvature radius	70 mm

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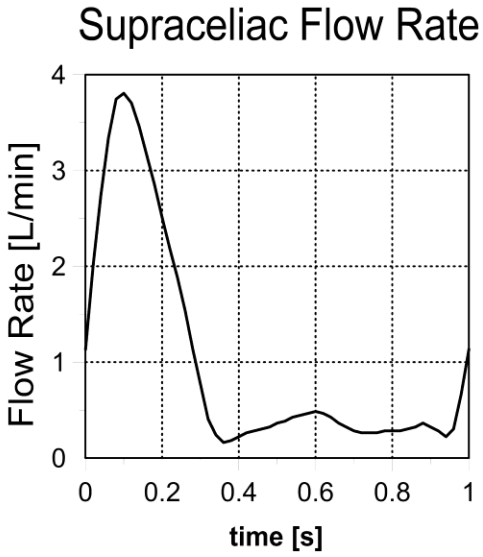
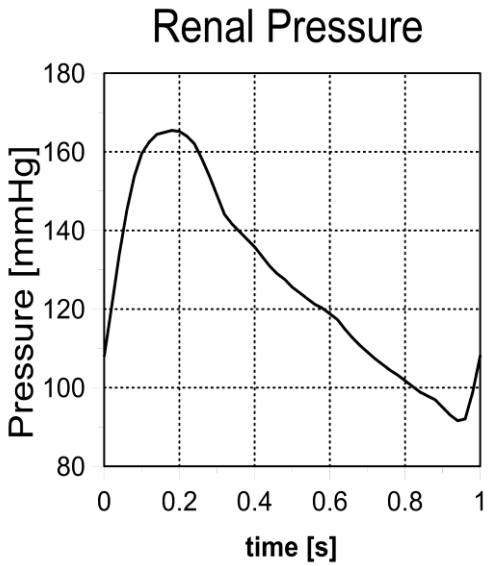
ENDOVASCULAR TECHNIQUES

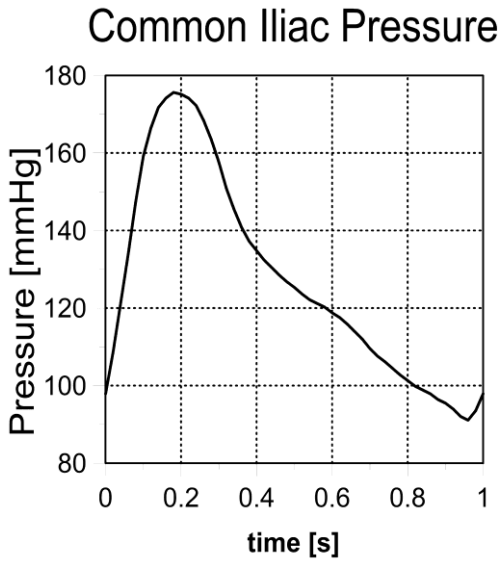
ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ
DEMOCRITUS UNIVERSITY OF THRACE

Γεωμετρία Μοντέλων & Οριακές Συνθήκες

Ταχύτητα εισόδου & πίεση εξόδου (boundary conditions)

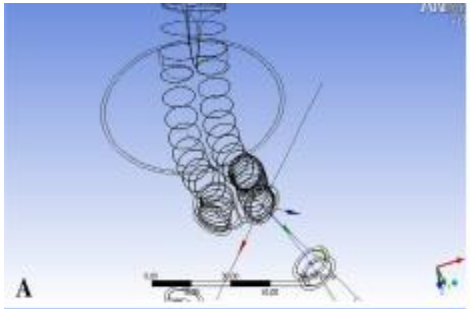


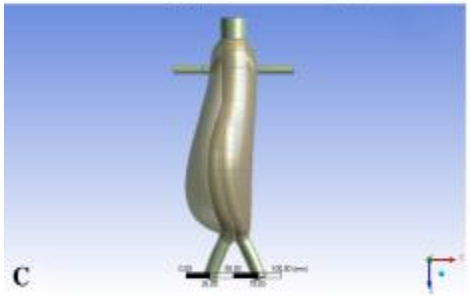


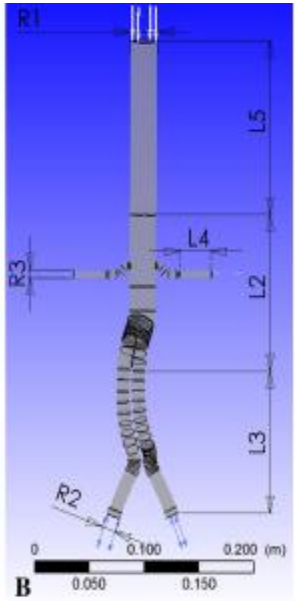


Figueroa et al, J Endovasc Ther 2009

Μεθοδολογία







Mesh generation (98,000 elements)
ANSYS version 12.1

- **Blood: Non-Newtonian (Carreau Yasuda model)**

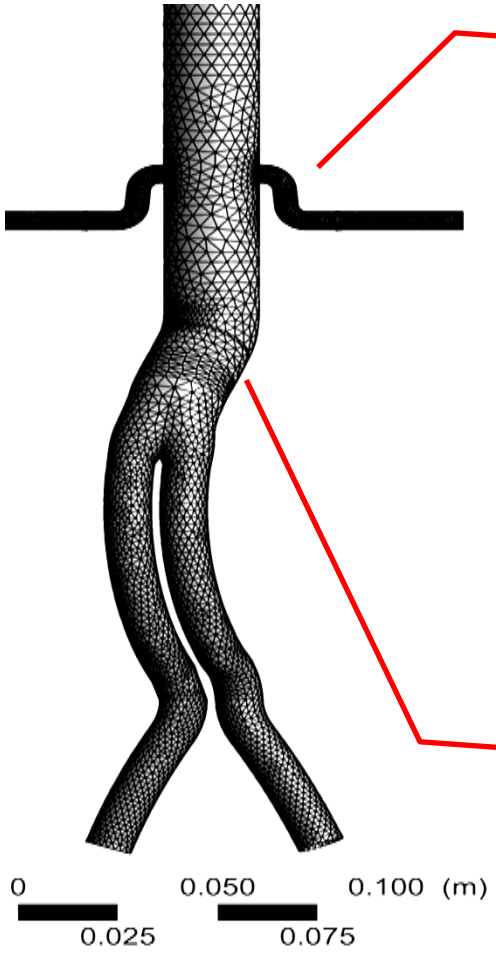
ANSYS

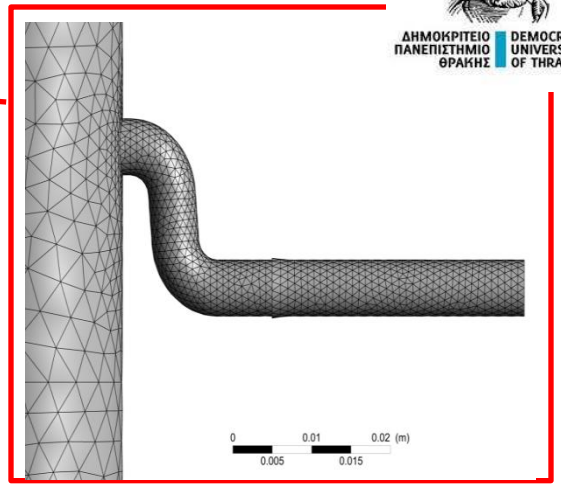
↓

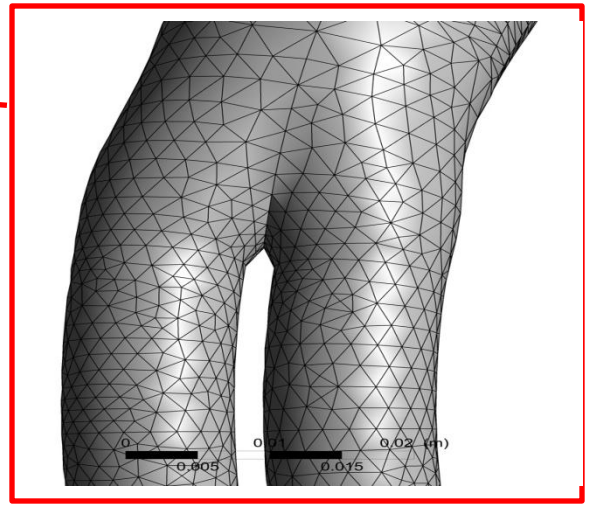
CFD

↙ ↘

DF **WSS**







ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

Αιμοδυναμικοί δείκτες- εξισώσεις

$$\mathrm{WSS} = \mu \frac{\partial u}{\partial y}$$

$$\mathrm{TAWSS} = \frac{1}{T}\int_0^T \left|\tau_w\right| \mathrm{d}t$$

$$\mathrm{OSI} = \frac{1}{2}\left(1 - \frac{\left|\int_0^T \tau_w \mathrm{d}t\right|}{\int_0^T \left|\tau_w\right| \mathrm{d}t}\right)$$

$$\mathrm{RRT} = \frac{1}{\frac{1}{T}\left|\int_0^T \tau_w \mathrm{d}t\right|}$$

$$\overrightarrow{F} = \sum_{i=1}^{N} \overrightarrow{F_{Pi}} + \overrightarrow{\tau_{w_i}} A_i$$

Mean exposure time:

$$\mathrm{MET}(e) = \frac{1}{N_e \sqrt[3]{V_e}} \sum_{p=1}^{N_p} \int_0^{\infty} H_e(p,t)\, \mathrm{d}t, \qquad H_e = \begin{cases} 1 \text{ if } x_p(t) \in e \\ 0 \text{ if } x_p(t) \notin e \end{cases}$$

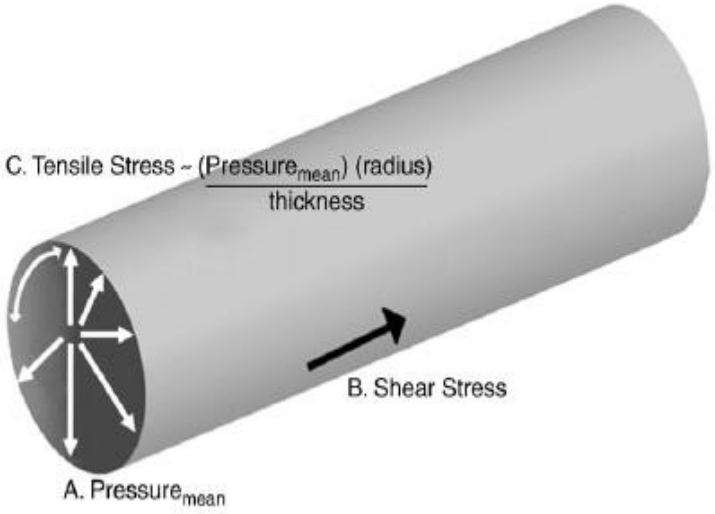
Arzani et al, Am J Physiol Heart Circ Physiol 2014; 307:H1786-95

Hemodynamic parameters – interpretations

Wall shear stress (WSS)	Associated with formation of intraluminal thrombus
Time-averaged wall shear stress (TAWSS)	integrating each nodal WSS magnitude over the cardiac cycle
Oscillatory shear index (OSI)	Indicates flow reversal: 0 (min) when WSS is unidirectional during cardiac cycle, 0.5 (max) when equal positive and negative WSS areas under the WSS vs. time curve
Relative residence time (RRT)	Measure of residence time of particles near the vessel wall. High values present regions with flow recirculation compared to regions with near-zero RRT
Mean exposure time (MET)	Measure of how long particles (platelets) entering the AAA from upstream are trapped near the wall

Georgakarakos et al, JVET 2019; 26: 250-7

ΕΙΣΑΓΩΓΗ ΣΤΗ ΜΗΧΑΝΙΚΗ ΤΩΝ ΑΝΕΥΡΥΣΜΑΤΩΝ



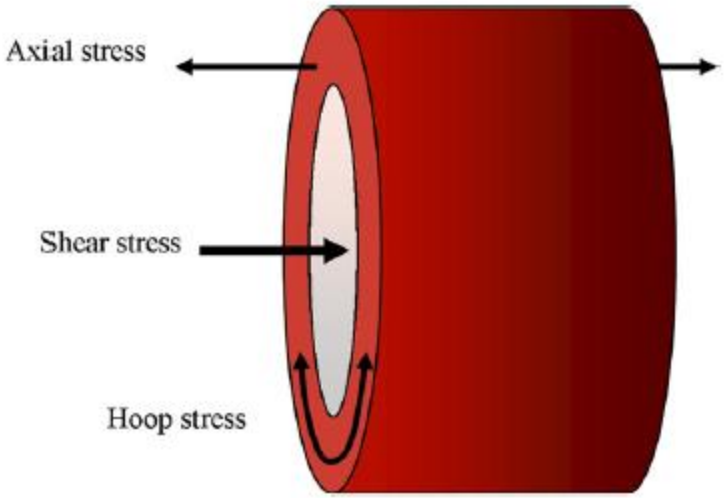
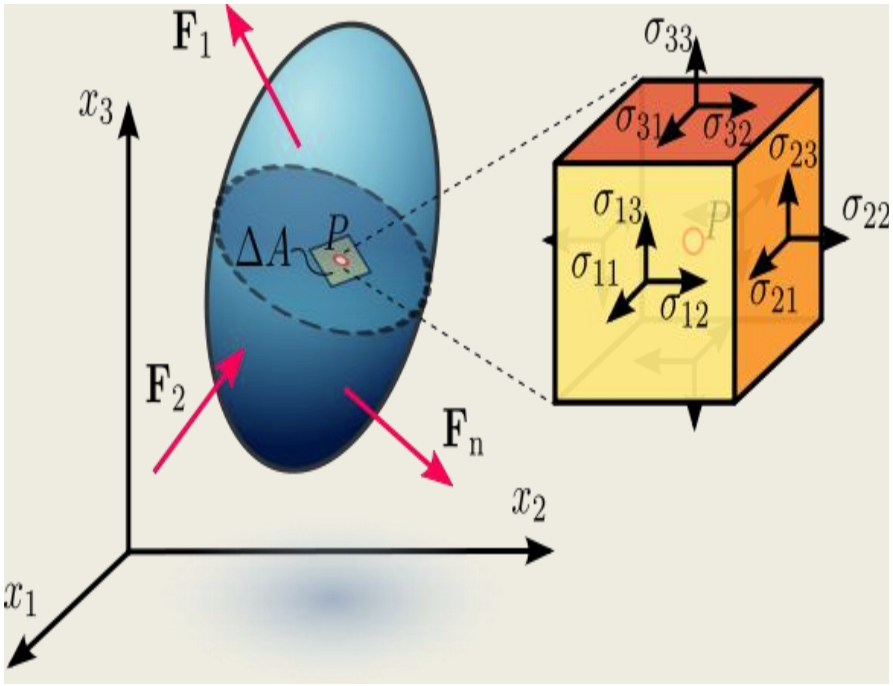


Fig 1. Forces acting on the aortic wall.



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

ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

Studying the Flow Dynamics Within Endografts in Abdominal Aortic Aneurysms

Efstratios Georgakarakos, Antonios Xenakis, George S. Georgiadis, Konstantinos C. Kapoulas, Evagelos Nikolopoulos and Miltos Lazarides

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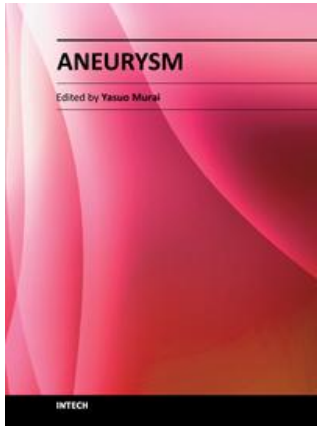


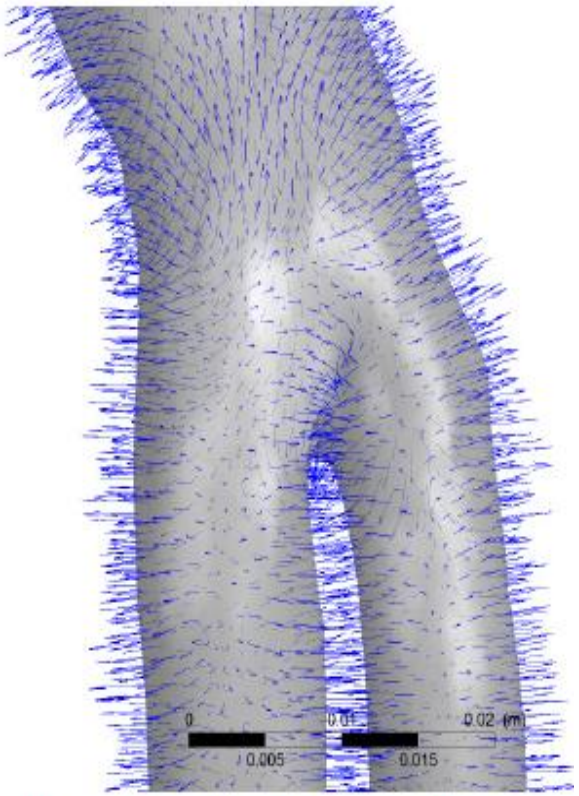


Figure 18. The pressure forces on the endograft bifurcation area (peak sys

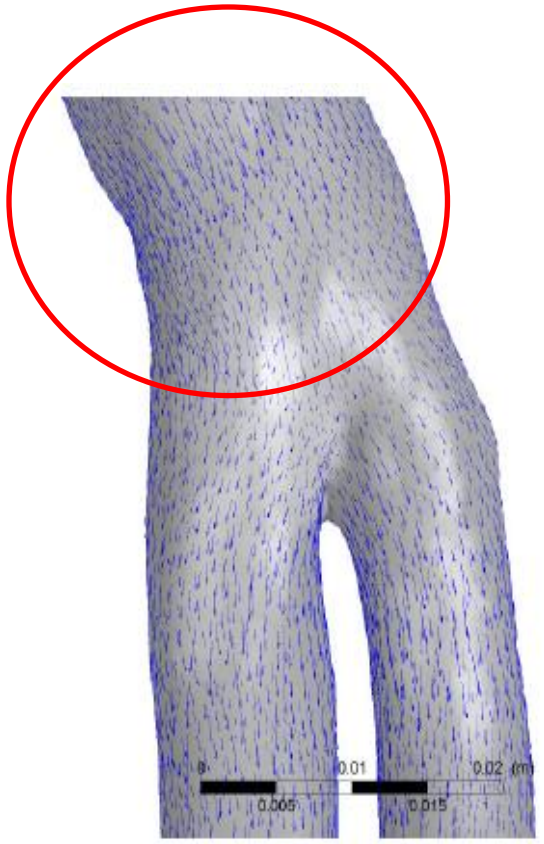


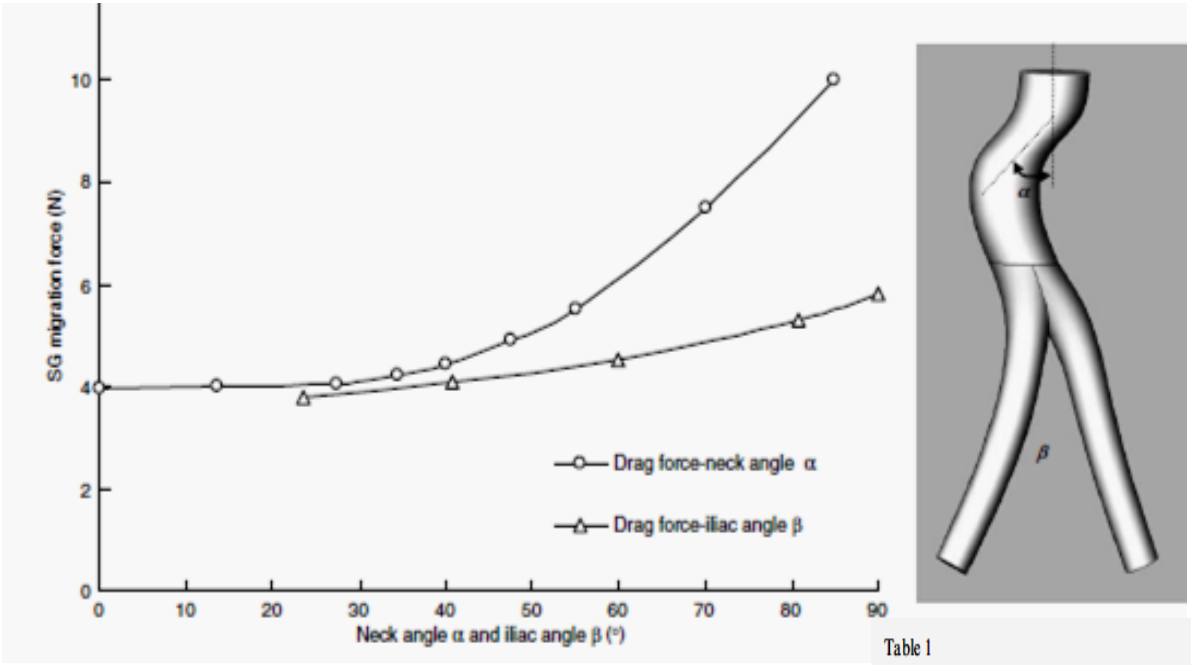
Figure 19. The tangential forces on the endograft bifurcation area (peak systolic phase).

ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

ΓΕΩΜΕΤΡΙΑ

- ✓ΥΠΟΝΕΦΡΙΚΟΣ ΑΥΧΕΝΑΣ
- ✓ΛΑΓΟΝΙΑ ΣΚΕΛΗ
- ✓ΚΑΜΠΥΛΟΤΗΤΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΟΣ

Παράγοντες που επηρεάζουν τη δύναμη μετανάστευσης



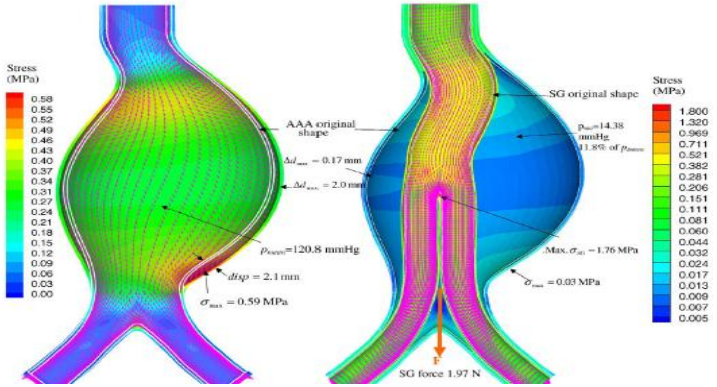
- ✓Γωνίωση αυχένα
- ✓Γωνίωση διχασμού
- ✓Διάμετρος ενδομοσχεύματος
- ✓Λόγος διαμέτρων αυχένα/λαγονίων

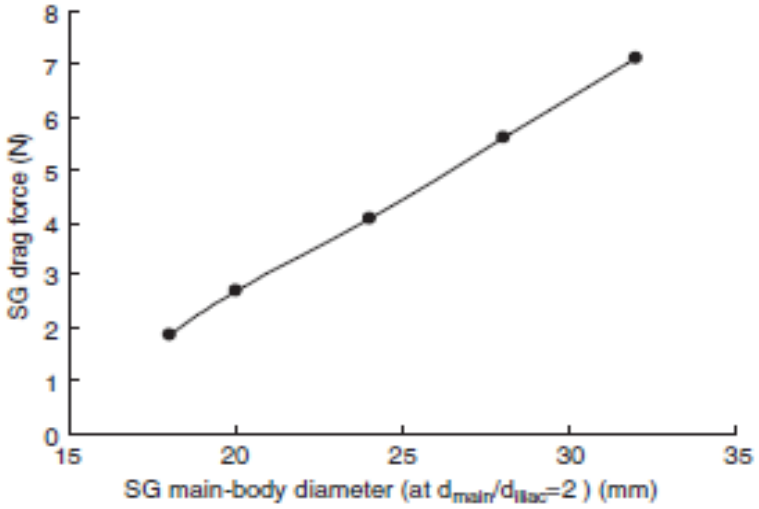
Table 1
Parameters required in the simulation

Parameters	Nonaneurysmal artery	Aneurysm	SG
Wall thickness (mm)	1.5	1.5–1.0 (Thubrikar et al., 2001)	Equivalent: 0.2
Diameter (mm)	Neck aorta (inner): 17 Iliac artery (inner): 11	60	Main body diameter: 17 Iliac leg: 11
Length (mm)	Neck aorta: 100 Iliac artery: 30	80	Main body: 60 Iliac leg: 70
Young's modulus (MPa)	1.2	4.66	Equivalent: 10
Poisson ratio	0.49	0.45	Equivalent: 0.27
Density (g/cm^3)	1.12	1.12	Equivalent: 6.0

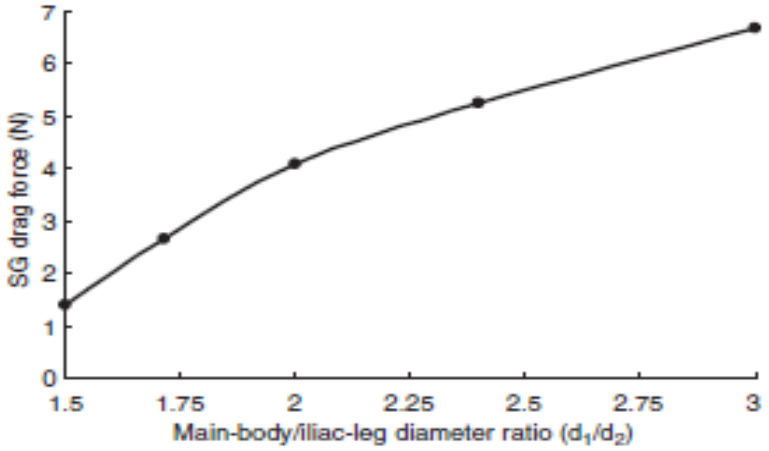
Li & Kleinstreuer, J Biomech, 2006; 39: 2264-73

Παράγοντες που επηρεάζουν τη δύναμη μετανάστευσης



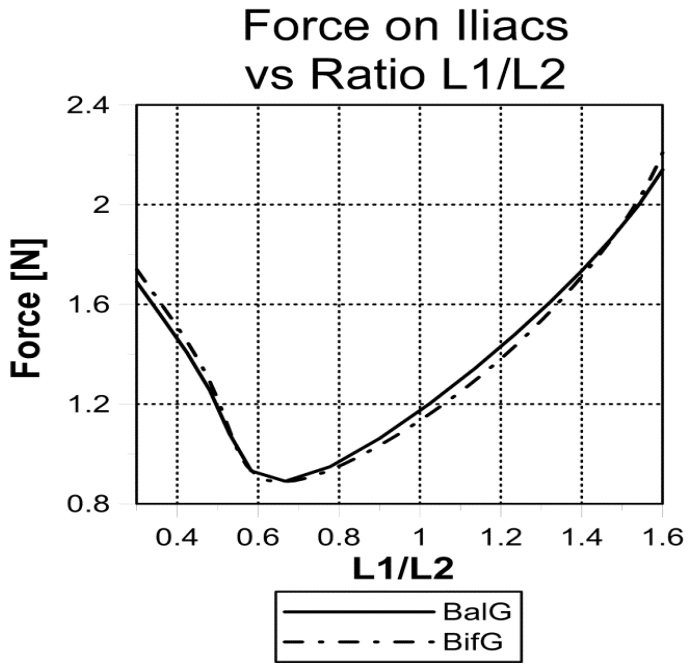


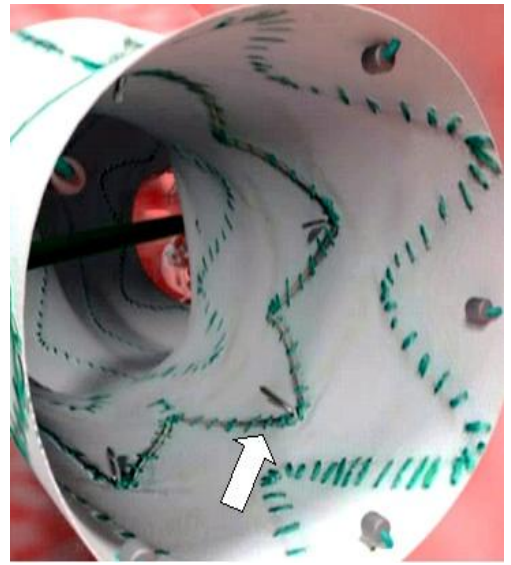
- ✓Γωνίωση αυχένα
- ✓Γωνίωση διχασμού
- ✓Διάμετρος ενδομοσχεύματος
- ✓Λόγος διαμέτρων αυχένα/λαγονίων



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

Αιμοδυναμικές παρατηρήσεις και βελτίωση ενδομοσχευμάτων





Ανάπτυξη σκελών με lock-stent (Treovance, Bolton)

Georgakarakos et al, Int Angiol; 2014: 480-4

Μέγιστη δύναμη: στο διχασμό

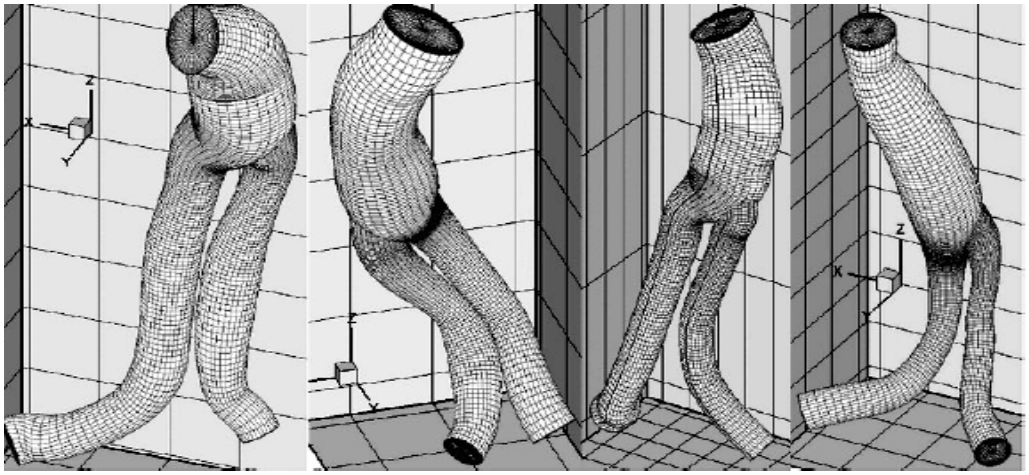
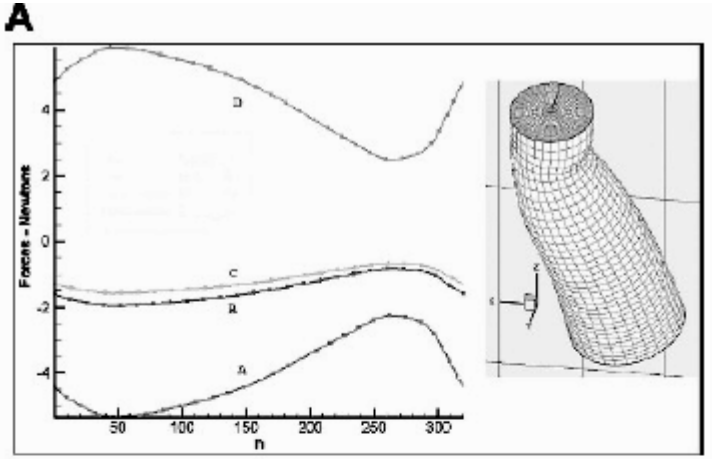
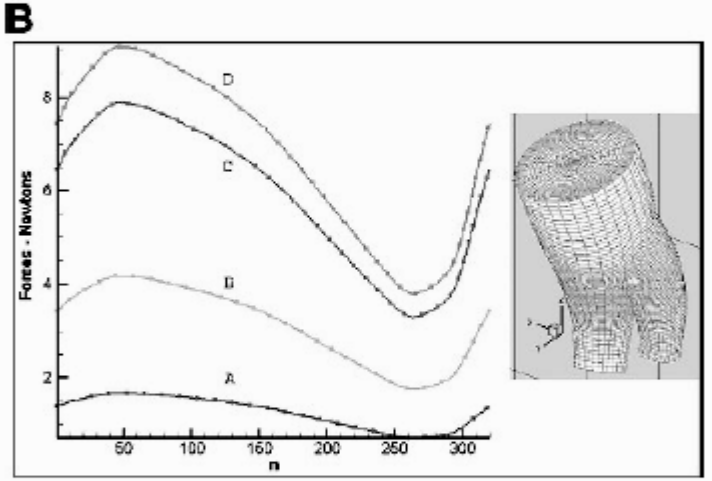


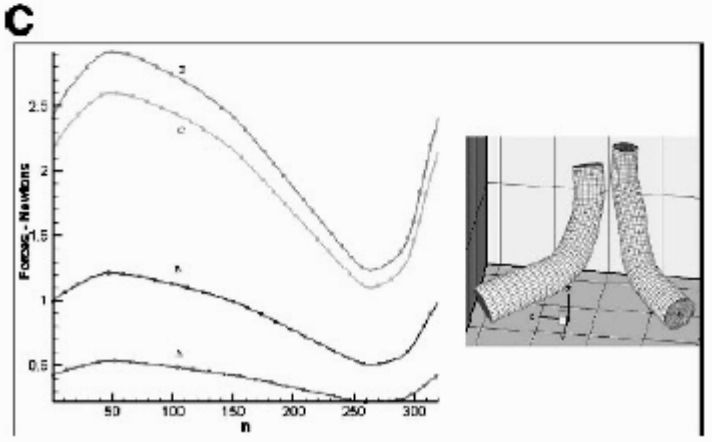
TABLE
Comparison of the Simulated Hemodynamic Forces Over the Total Stent-Graft and the Bifurcation Component for All 4 Patients

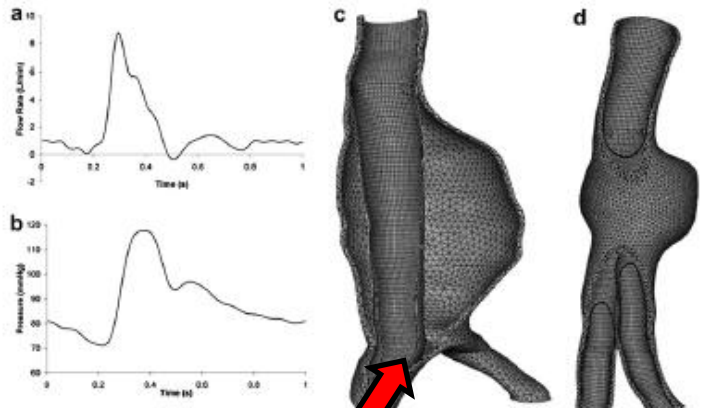
	Total Force, N		Caudal Force, N	
	Stent-Graft	Bifurcation	Stent-Graft	Bifurcation
Patient A	6	4.4	~0	4
Patient K	8.4	6.4	6	5.2
Patient M	6.3	8.4	4.1	6.8
Patient S	2.4	3.8	2	2.8

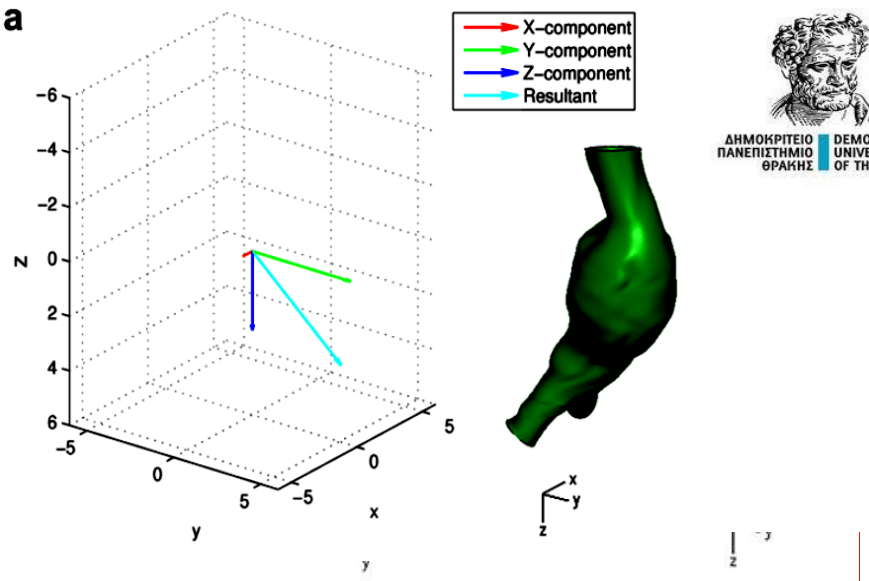
Howell et al, JEVT, 2007; 14:138-43

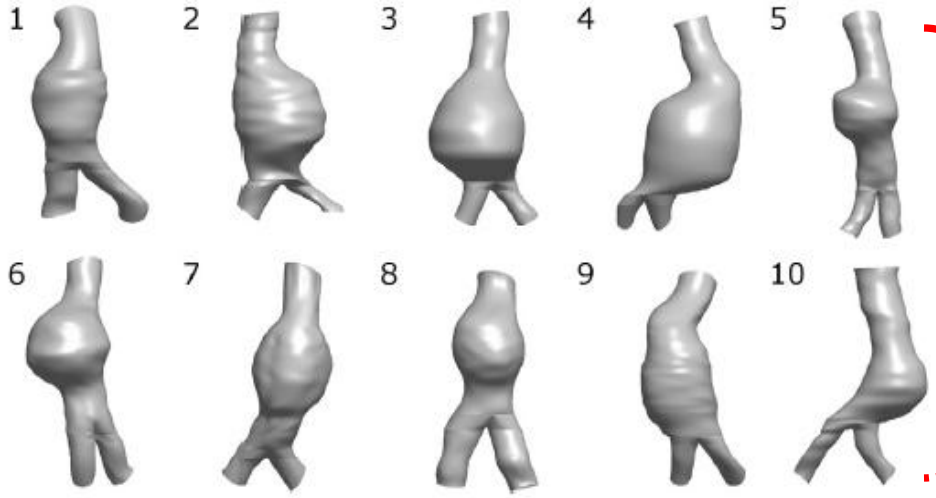












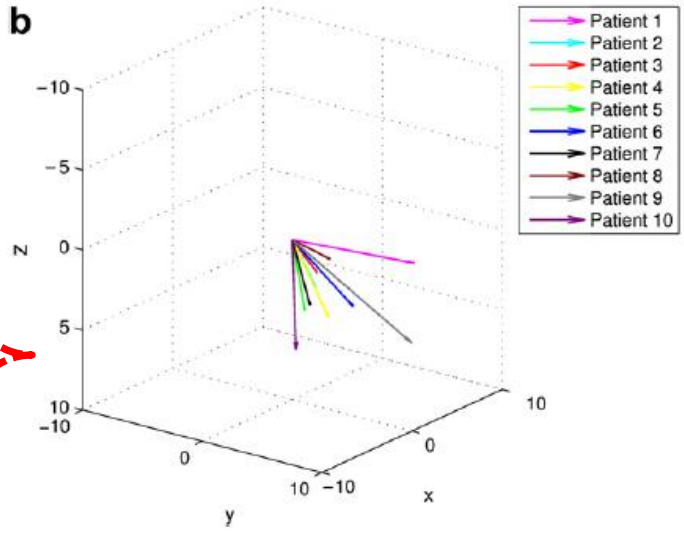
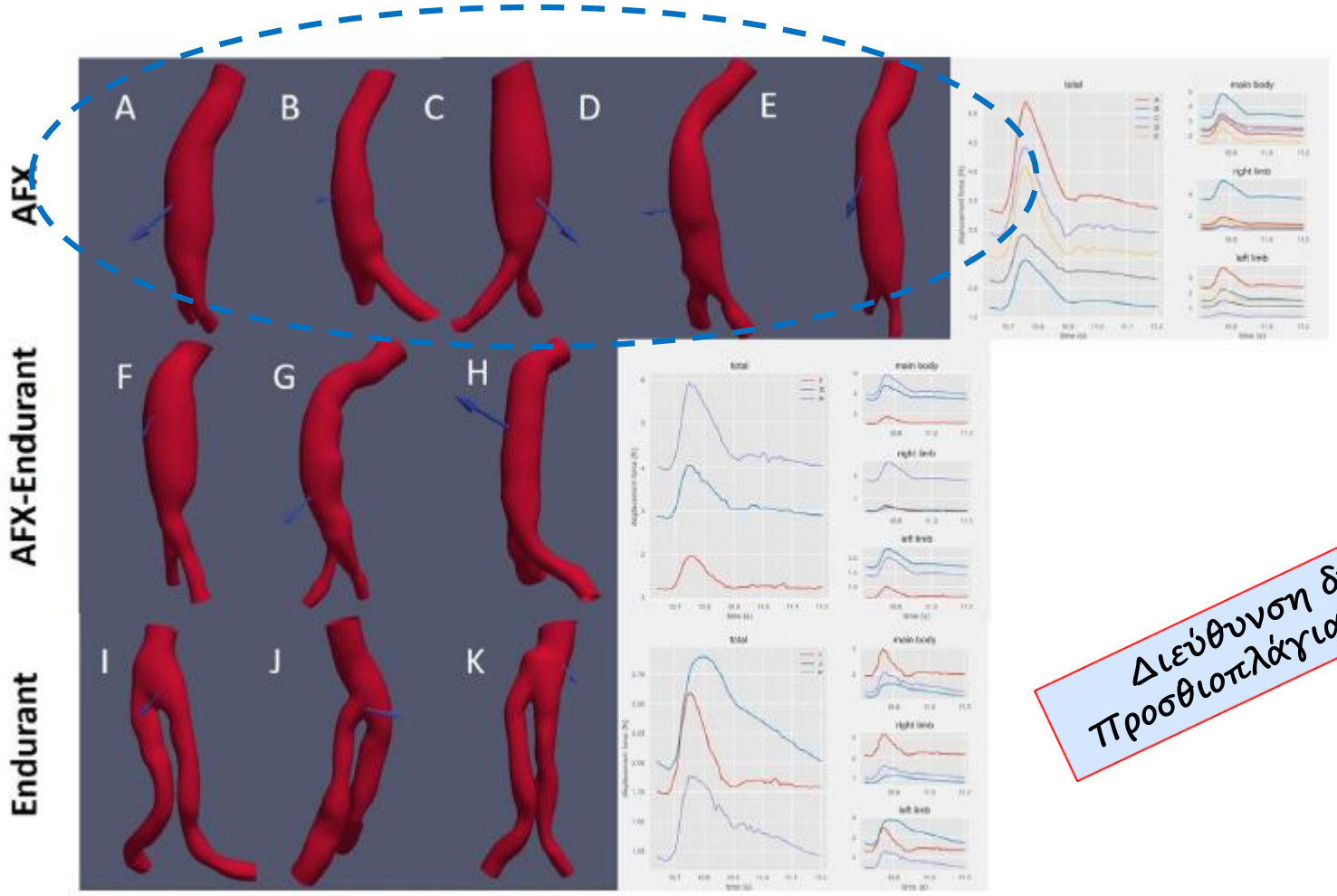


Figure 1 Aneurysm geometry from all 10 patients.

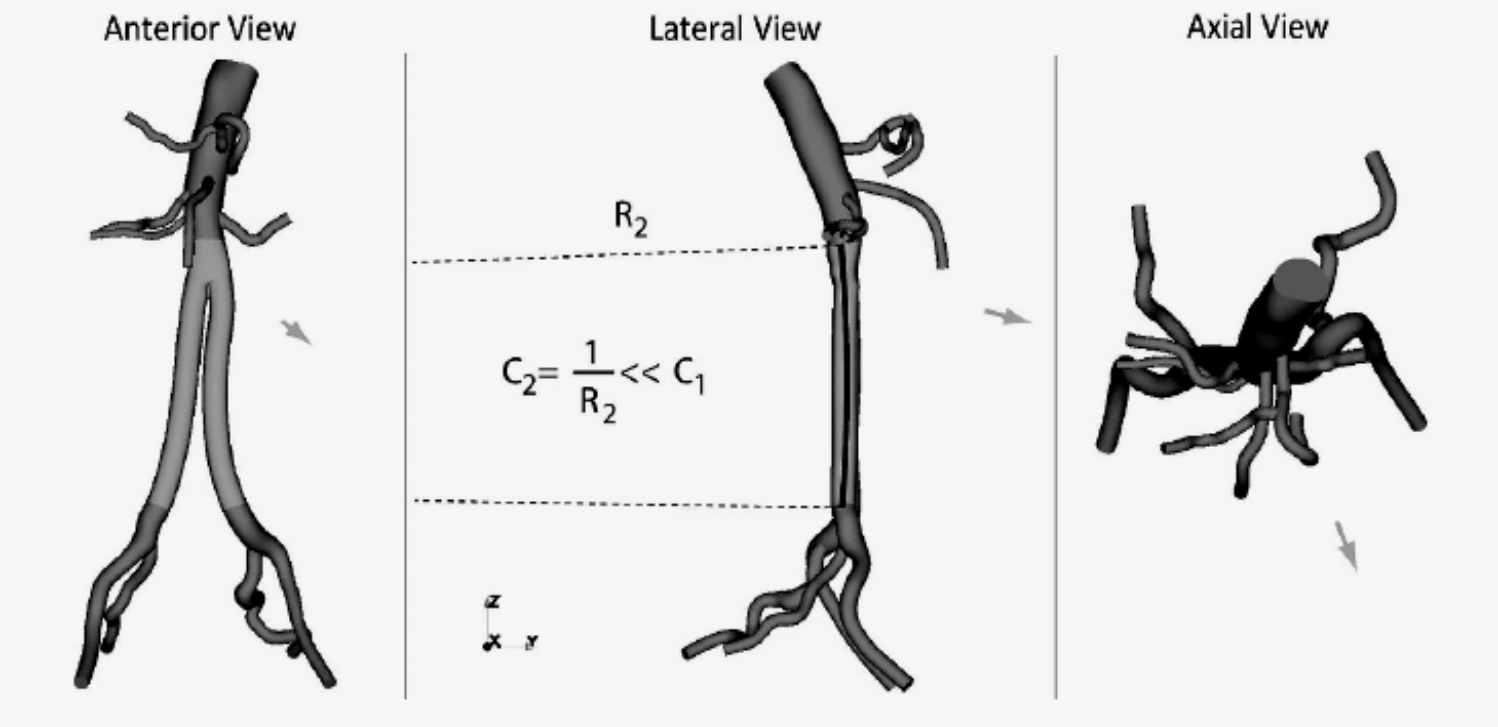
Διεύθυνση δυνάμεων:
Προσθιοπλάγια παρά κάθετη

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



Διεύθυνση δυνάμεων:
Προσθιοπλάγια παρά κάθετη

Ioannidis et al, Ann Vasc Surg, 2021; 74:400-9

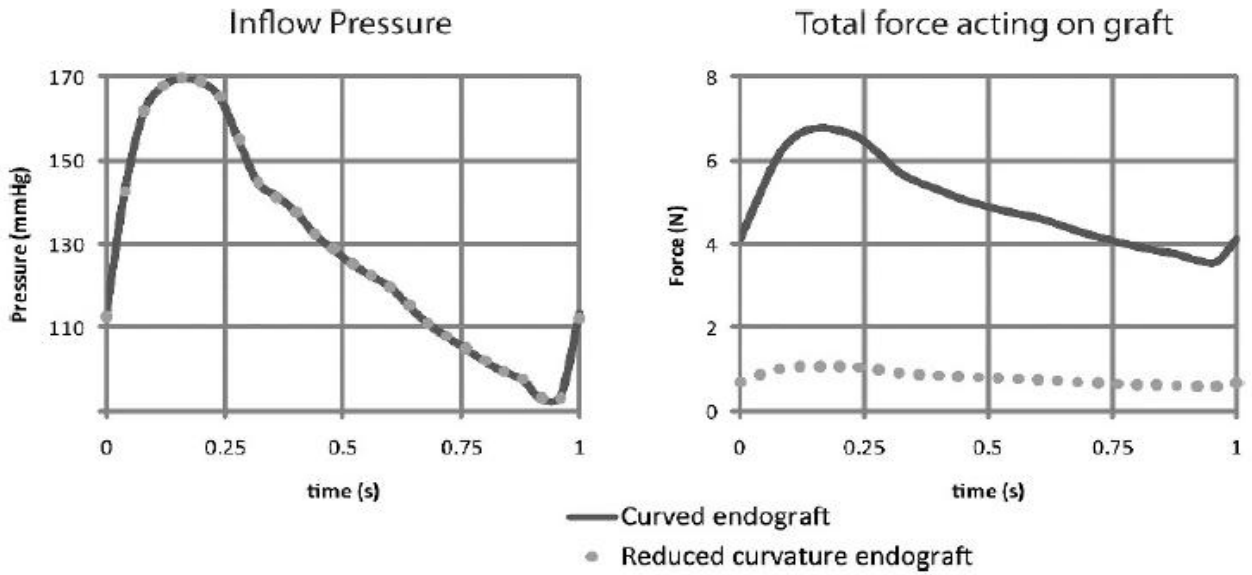


Επίδραση της καμπυλότητας του σώματος του ενδομοσχεύματος

ENDOGRAFT CURVATURE AND DISPLACEMENT FORCES
Figueroa et al.

J ENDOVASC THER
2009;16:284–294

Επίδραση της καμπυλότητας του σώματος του endograft

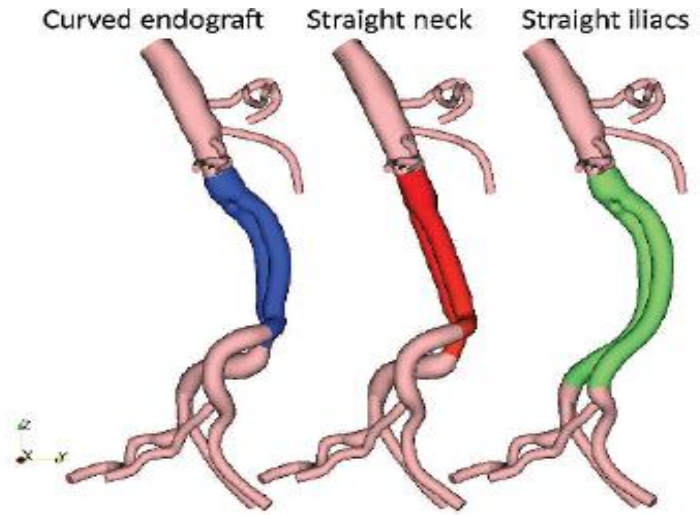


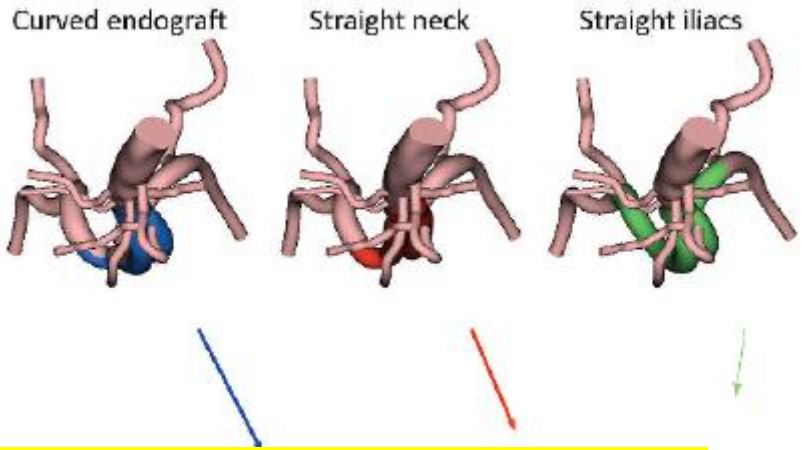
Η καμπυλότητα του ενδομοσχεύματος αυξάνει την μεταναστευτική δύναμη

ENDOGRAFT CURVATURE AND DISPLACEMENT FORCES
Figueroa et al.

J ENDOVASC THER
2009;16:284–294

Επίδραση της γωνίωσης αυχένα και λαγονίων





Ευθύς αυχένας ή/και ευθεία λαγόνια σχετίζονται με ελάττωση των μεταναστευτικών δυνάμεων

Η διαμόρφωση του αυχένα / λαγονίων επηρεάζει το μέγεθος και διεύθυνση των μεταναστευτικών δυνάμεων

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

JOURNAL OF ENDOVASCULAR THERAPY
A SAGE Publication
Journal of Endovascular Therapy
2017, Vol. 24(3) 411–417
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www.jevt.org
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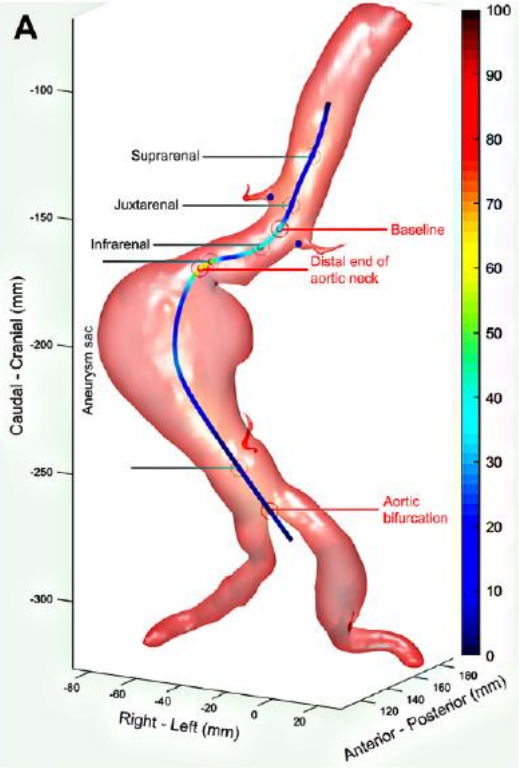
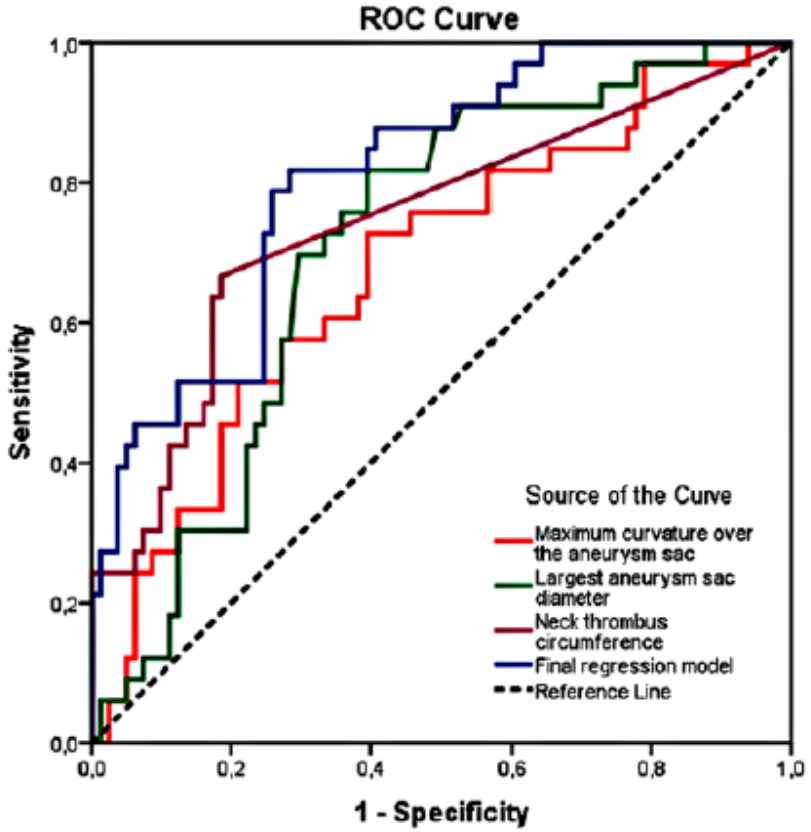
ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

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

Όψιμη μετανάστευση!!!





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

ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

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

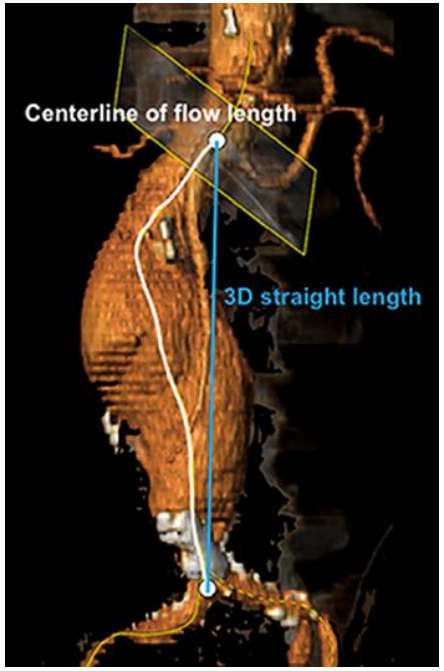
Abstract

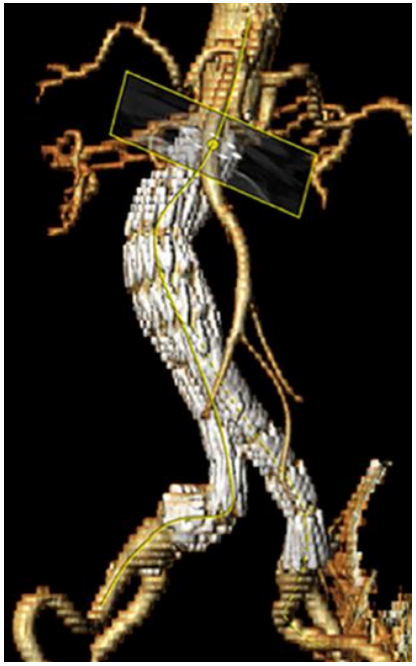
BACKGROUND: Endovascular aneurysm repair (EVAR) becomes the treatment of choice for patients with abdominal aortic aneurysm (AAA). Type I or III endoleak is related to high risk of rupture and reintervention, but little is known about the delayed presentation of these. We sought to evaluate the delayed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





Eur J Vasc Endovasc Surg (2019) 58, 538–547

Endograft Specific Haemodynamics After Endovascular Aneurysm Repair: Flow Characteristics of Four Stent Graft Systems

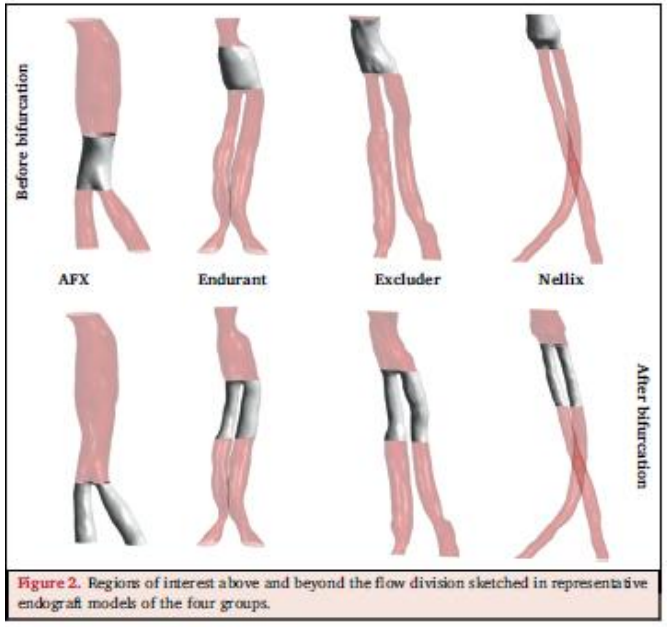
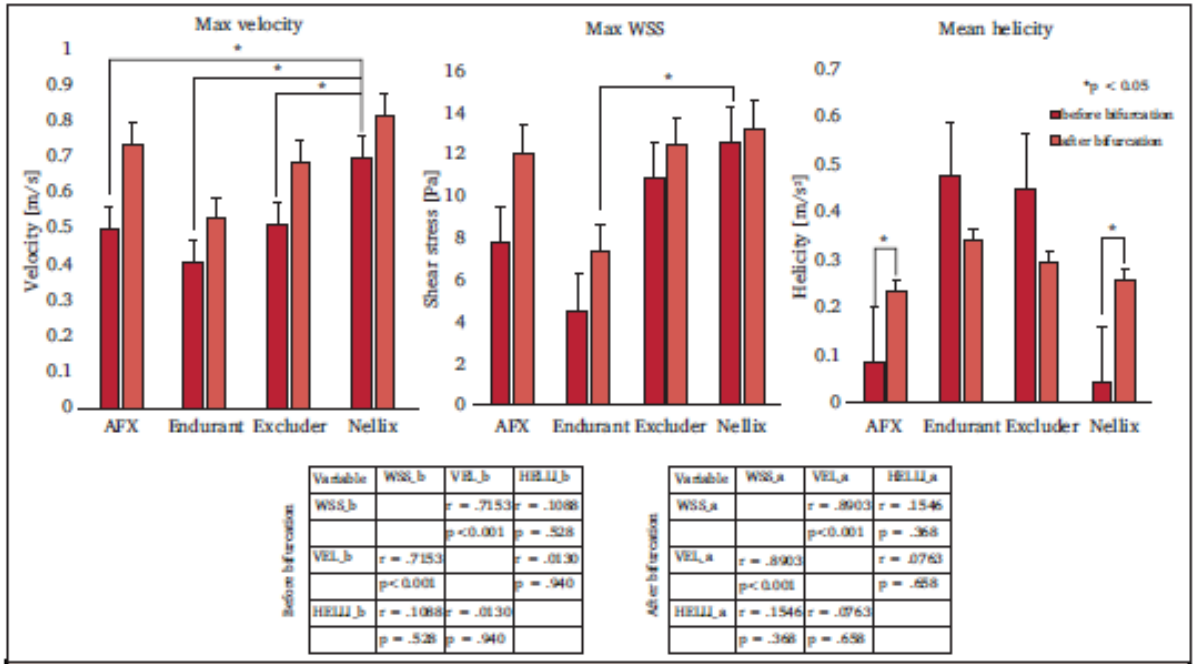


Figure 2. Regions of interest above and beyond the flow division sketched in representative endograft models of the four groups.



Below bifurcation

Variable	WSS_b	VEL_b	HELI_b
WSS_b		r = .7153	r = .1088
		p<0.001	p = .528
VEL_b	r = .7153		r = .0130
	p<0.001		p = .940
HELI_b	r = .1088	r = .0130	
	p = .528	p = .940	

After bifurcation

Variable	WSS_a	VEL_a	HELI_a
WSS_a		r = .8903	r = .1546
		p<0.001	p = .368
VEL_a	r = .8903		r = .0763
	p<0.001		p = .658
HELI_a	r = .1546	r = .0763	
	p = .368	p = .658	

Figure 3. Mean and SE values of the haemodynamic indices [velocity, wall shear stress (WSS), helicity] in both regions of interest in the four endograft groups. The asterisk indicates statistical significance. Below the charts, two tables with *r* and *p* values from the correlation analysis for the pairs of haemodynamics variables under consideration, where the indices "_b" and "_a" are attached to the variable names to indicate calculation before and after the bifurcation zone, respectively.

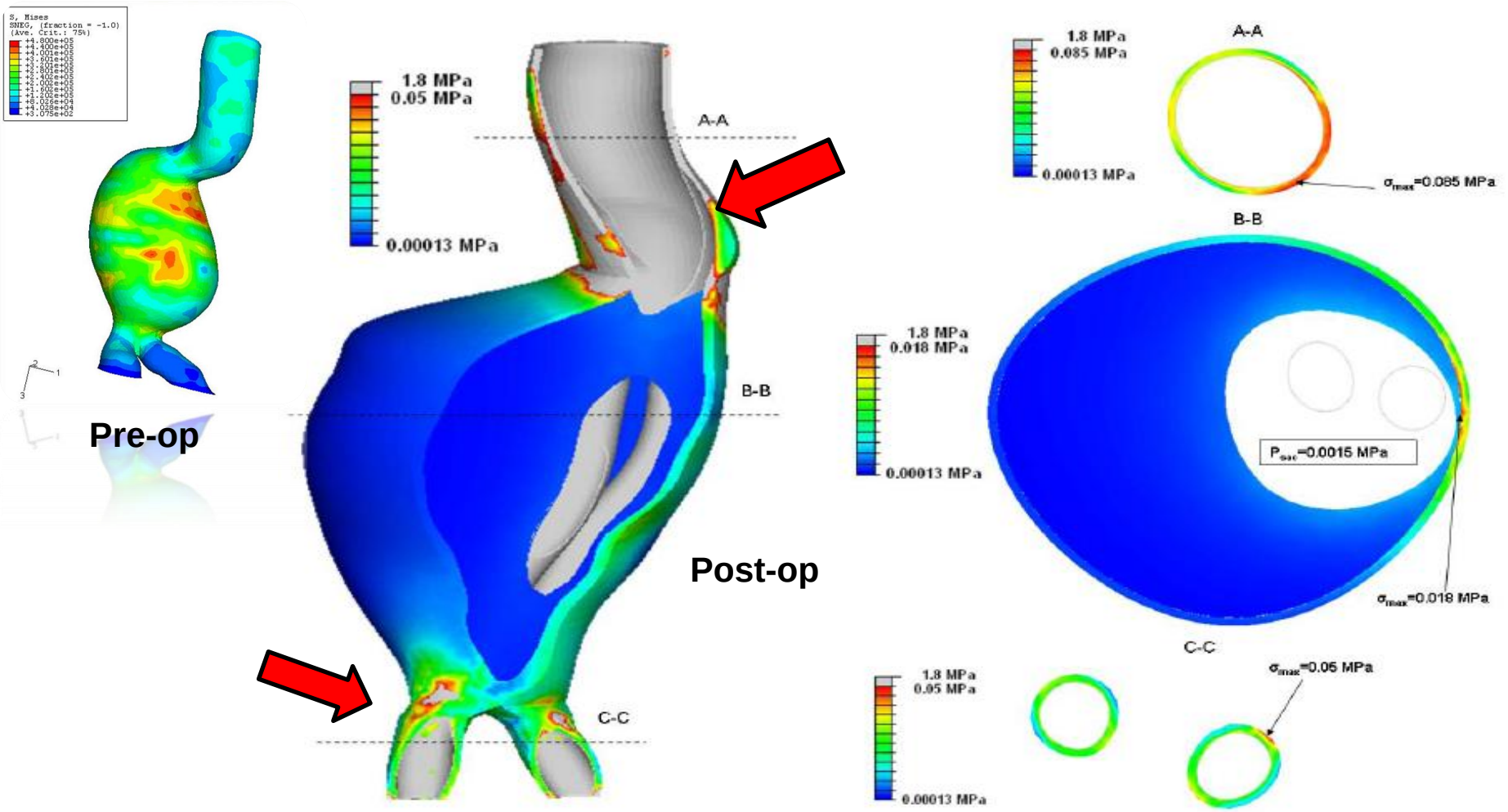
1. Διαφορετικές γεωμετρίες επάγουν διαφορετικές αιμο-ρεολογικές συμπεριφορές (WSS, ταχύτητα, ελικότητα)
2. Κοντό main body & σκληρό υλικό (Endurant) επάγει ↓ WSS και ταχύτητα αλλά ↑ ελικότητα
3. Nellix το υψηλότερο WSS
4. Ελικότητα ↑ σε Endurant & Excluder αλλά ↓ σε AFX & Nellix
5. AFX & Excluder: ίδιες αιμοδυναμικές συμπεριφορές (απότοκο PTFE??)

ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

REMODELLING

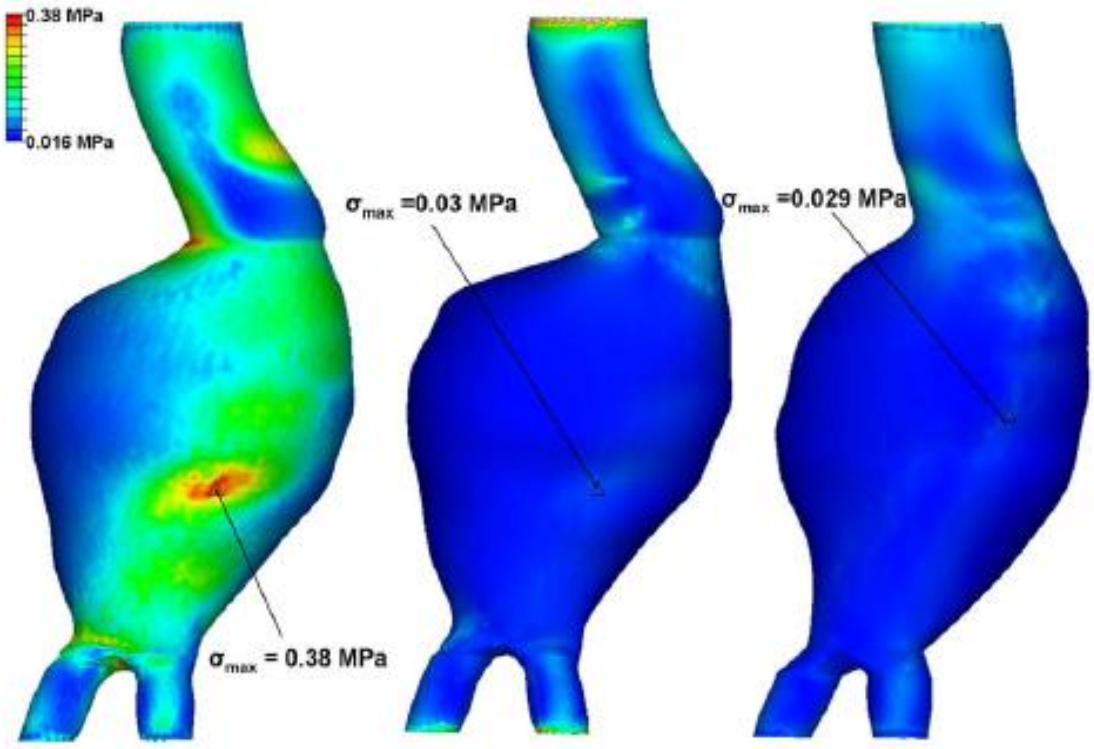
- ✓ΜΗΧΑΝΙΚΕΣ ΙΔΙΟΤΗΤΕΣ
- ✓ΔΥΝΑΜΕΙΣ
- ✓ΤΑΣΕΙΣ
- ✓ΓΕΩΜΕΤΡΙΑ

PWS (μέγιστη τοιχωματική τάση): ανακατανομή από το σάκο προς αυχένα & λαγόνια



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

Μετεγχειρητική Συμπεριφορά του ΑΑΑ



Προεγχ. | Άμεσα μετεγχειρητικά | 6 μήνες

- ✓PWS ελαττώνεται
- ✓ΑΑΑ ενδοτικότητα ελαττώνεται
- ✓Μετεγχειρητικό remodeling οδηγεί σε ανακατανομή τάσεων

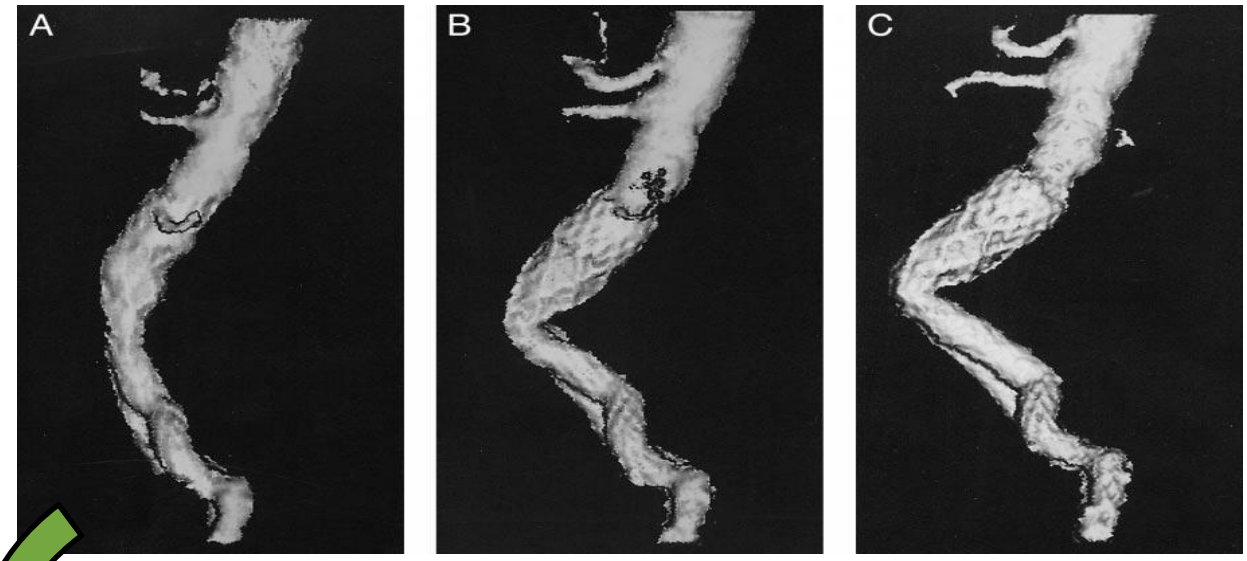
⇩

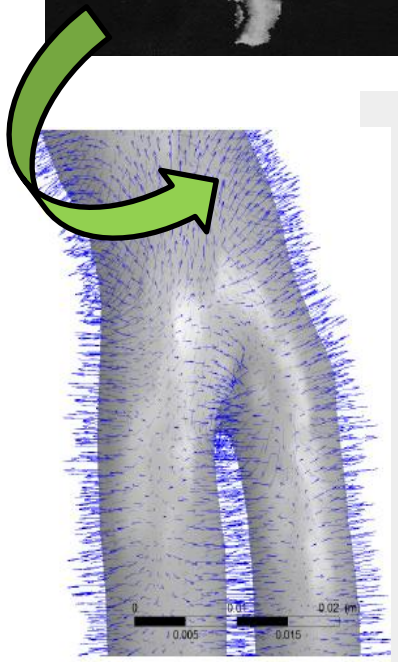
- ✓Ουραία μετανάστευση…

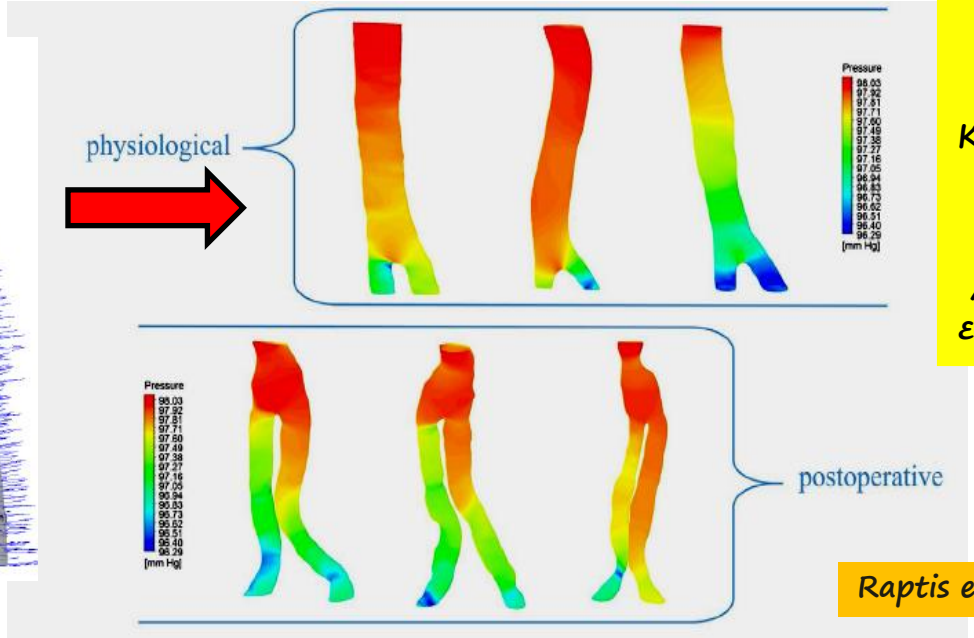
Molony et al, J Biomed Eng Online, 2009; 8:24

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

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







Remodelling:
Αλλαγή στον ανευρυσματικό σάκο φέρνει αλλαγές στο ενδομόσχευμα

⇅

Ελάττωση γωνίωσης αυχένα ΚΑΙ λαγονίων

⇅

Καμπυλότητα endograft

⇅

Αναδιανομή δυνάμεων στο ενδομόσχευμα

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

Remodelling: ελάττωση γωνίωσης αυχένα ΚΑΙ λαγονίων

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

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

J ENDOVASC THER
2001;8:34–38

Ελάττωση γωνίωσης αυχένα λόγω remodelling

◆ 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]

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

J ENDOVASC THER
2010;17:594–598

Ελάττωση ελίκωσης λαγονίων λόγω remodelling

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

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

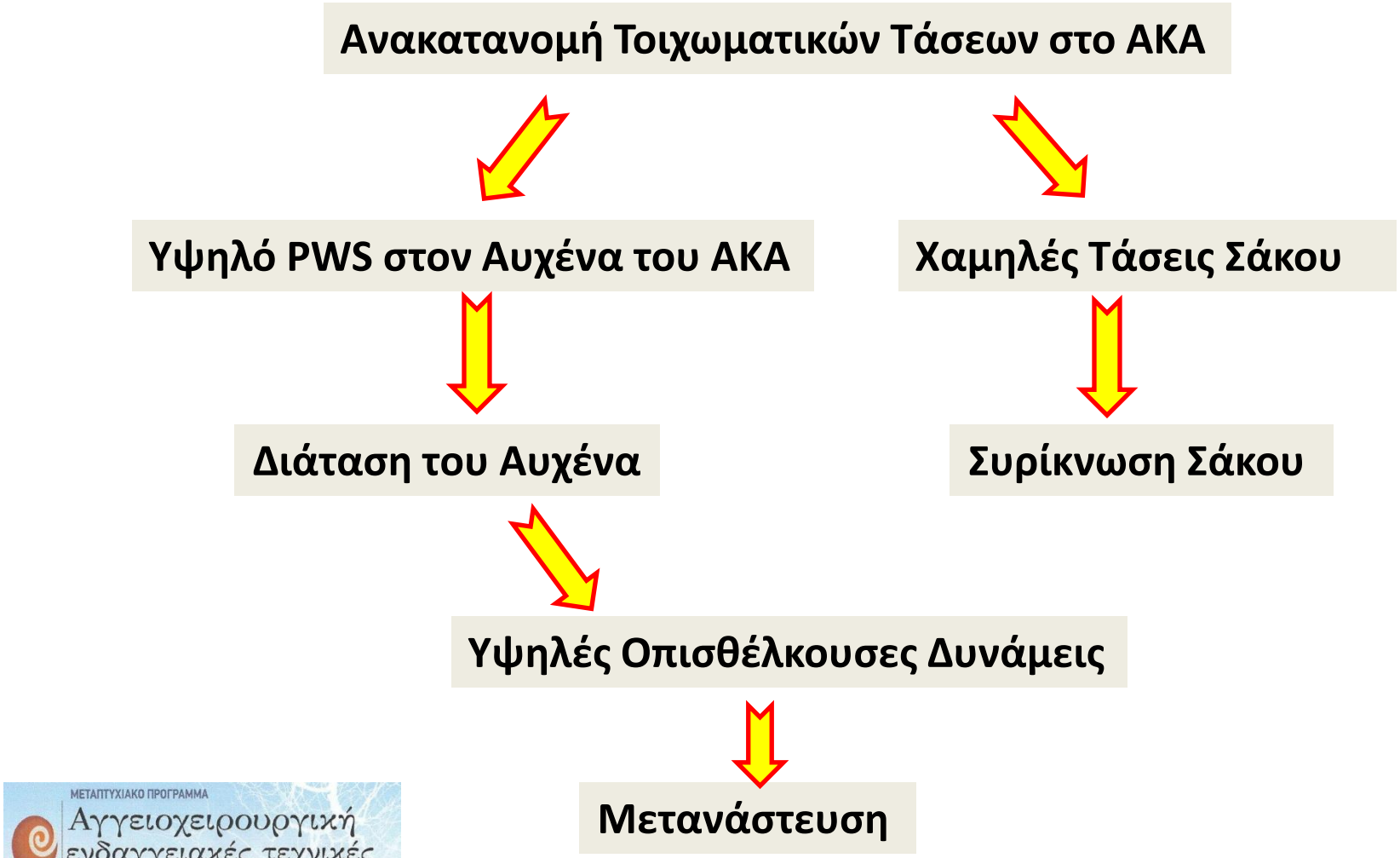
James Coulston, MSc, FRCS,[a] Amy Baigent, MBBS,[a] Haran Selvachandran,[b] Steven Jones, MRCS,[a,b] Francesco Torella, MD, FRCS,[a] and Robert Fisher, MD, FRCS,[a] *Liverpool, United Kingdom*

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)

ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

Εξελιξη της Αιμοδυναμικης Συμπεριφορας του Ανευρυσματος



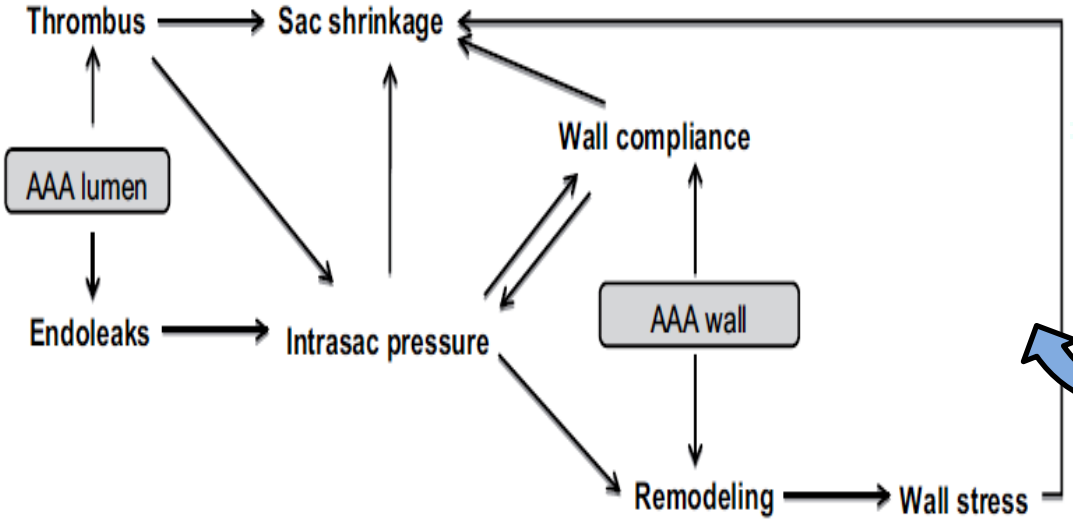
ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ
DEMOCRITUS UNIVERSITY OF THRACE

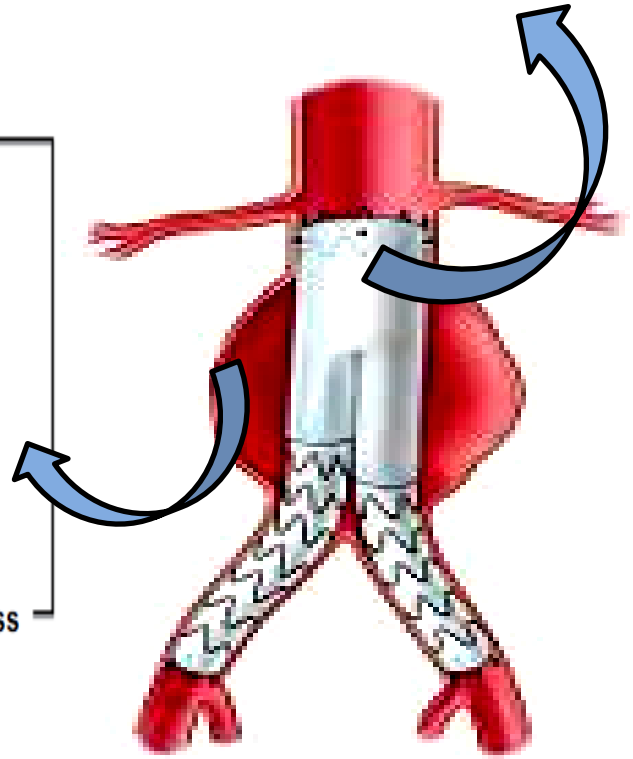
ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

ΣΑΚΟΣ +ΕΝΔΟΜΟΣΧΕΥΜΑ= ΣΥΖΕΥΓΜΕΝΟ ΣΥΣΤΗΜΑ !!

Safe…but not too safe!
Simple…but not too simple!

μορφολογικές αλλαγές





Georgakarakos et al, Vasc Med 2012

ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

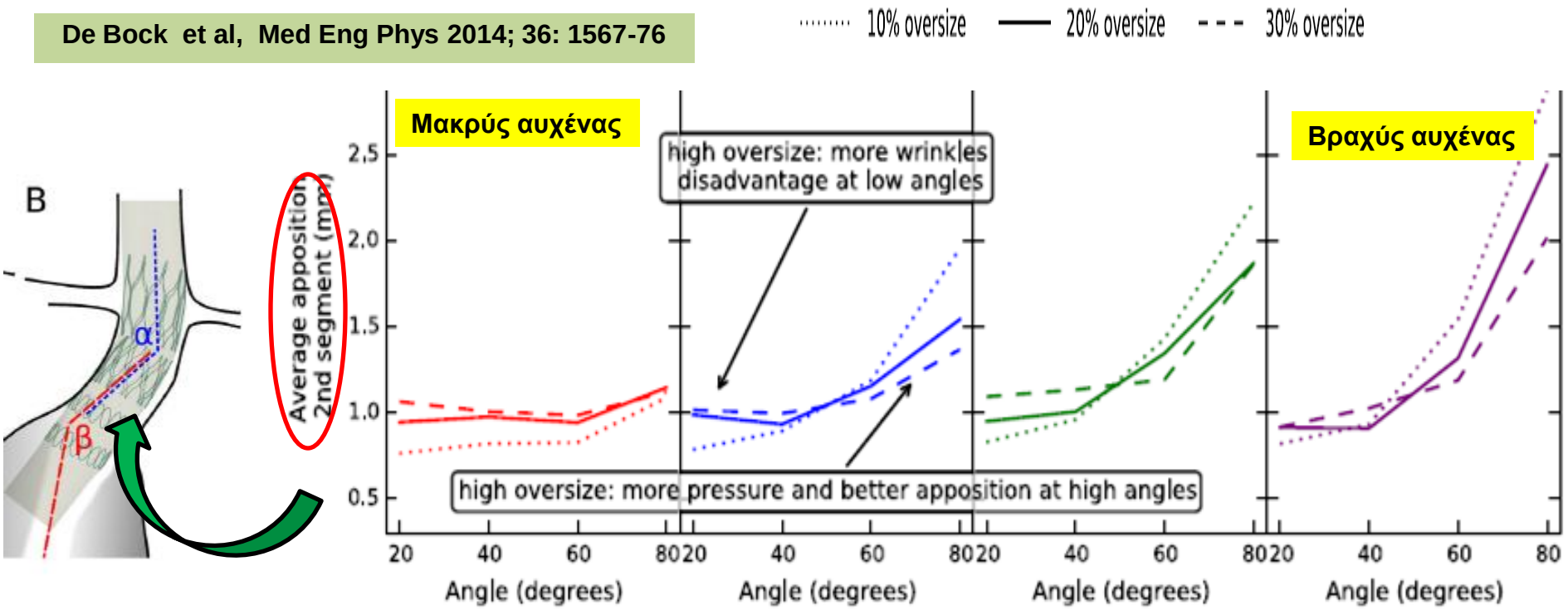
ΥΠΟΝΕΦΡΙΚΟΣ ΑΥΧΕΝΑΣ

- ✓ΚΕΝΤΡΙΚΗ ΠΡΟΣΦΥΣΗ
- ✓ΚΑΤΑΝΟΜΗ ΔΥΝΑΜΕΩΝ
- ✓ΒΕΛΤΙΩΣΕΙΣ & ΤΡΟΠΟΠΟΙΗΣΕΙΣ

Η γωνίωση του αυχένα επιδρά στην : 1) εναπόθεση του stent

2) κατανομή δυνάμεων

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

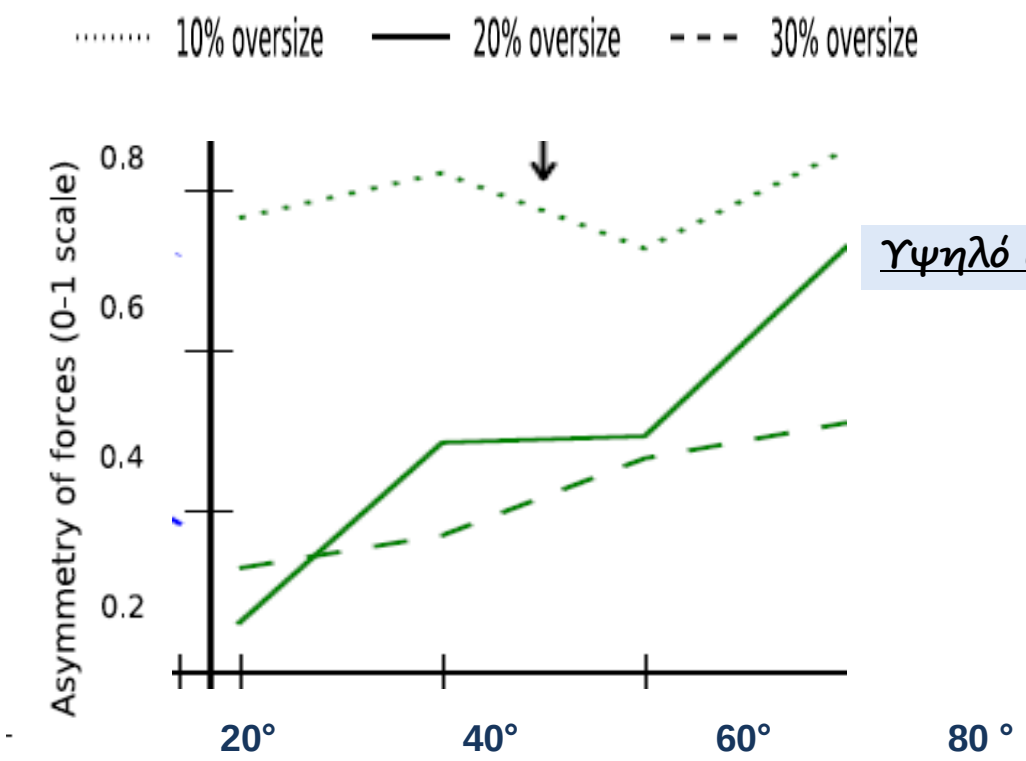


Βραχύς αυχένας ± Μεγάλη γωνίωση→ ανάγκη για μεγάλο oversizing ώστε→ καλύτερη πρόσφυση (apposition)

Υψηλό oversizing → μεγάλες ακτινικές δυνάμεις

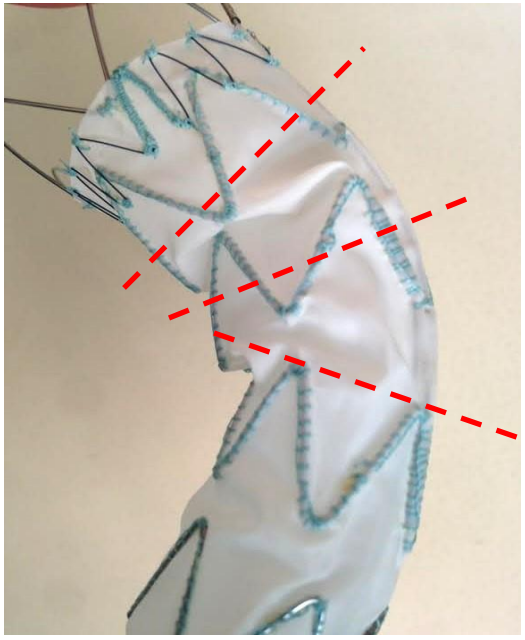
Η γωνίωση του αυχένα επιδρά στην : 1) εναπόθεση του stent

2) κατανομή δυνάμεων

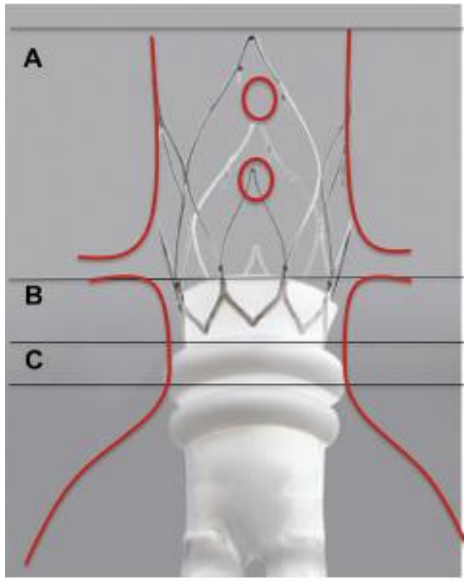


Χαμηλό oversizing (i.e., 10%) ευθύνεται για σημαντική ασυμμετρία των δυνάμεων στον αυχένα

Υψηλό oversizing → μεγάλες ακτινικές δυνάμεις



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



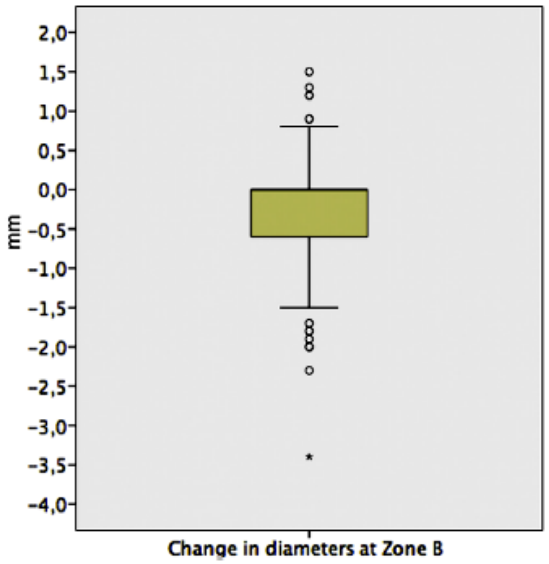


Fig 5. Zone B: changes in diameters over time. The *horizontal line* in the middle of the box indicates the median; the *top and bottom borders* of the box mark the 75th and 25th percentiles, respectively, and the *whiskers* mark the 90th and 10th percentiles.

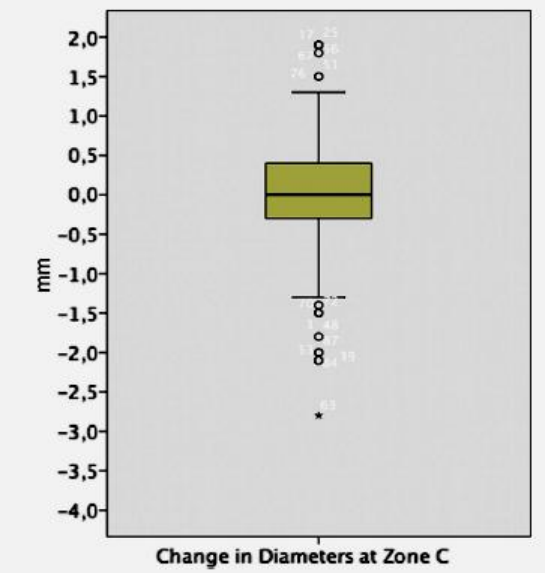
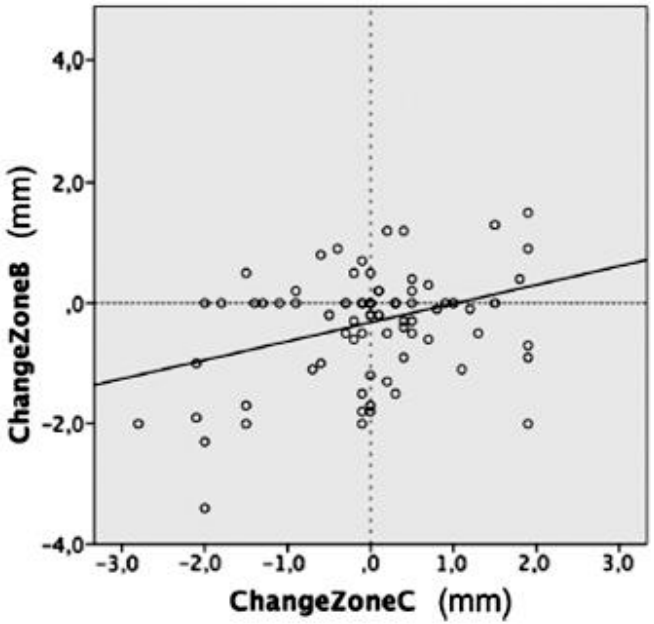


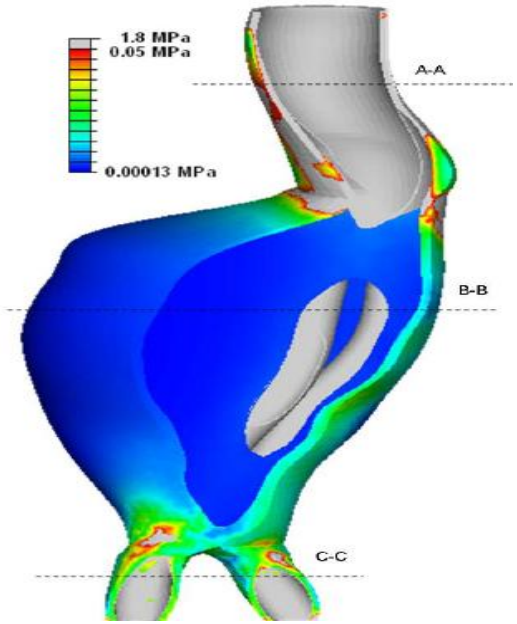
Fig 6. Zone C: changes in diameters over time. The *horizontal line* in the middle of the box indicates the median; the *top and bottom borders* of the box mark the 75th and 25th percentiles, respectively, and the *whiskers* mark the 90th and 10th percentiles.

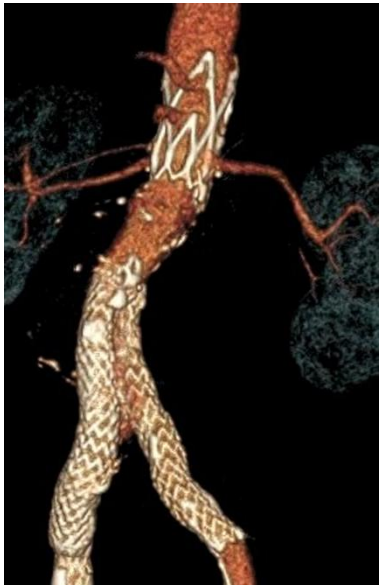


Η εφαρμογή δακτυλίων πολυμερούς για σφράγιση & απουσία εφαρμογής ακτινικής δύναμης από Nitinol στον υπονεφρικό αυχένα οδηγεί ακόμη και σε συρρίκνωση της διαμέτρου!

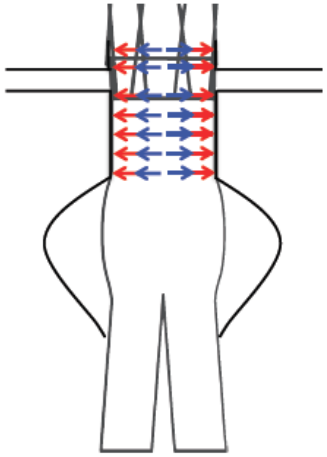
(De Donato et al., JVS 2016; 63:8-15)

Αιμοδυναμικές παρατηρήσεις και βελτίωση ενδομοσχευμάτων – Παράδειγμα ΙΙ



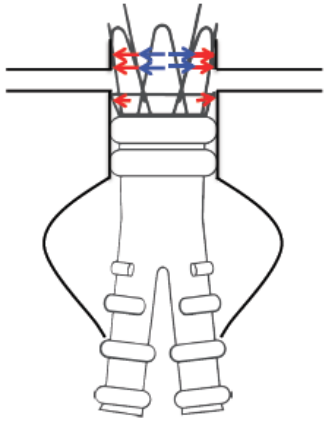


Self Expanding Stent Graft
Oversized wire and fabric graft allows transmission of blood pressure, and exerts pressure of its own

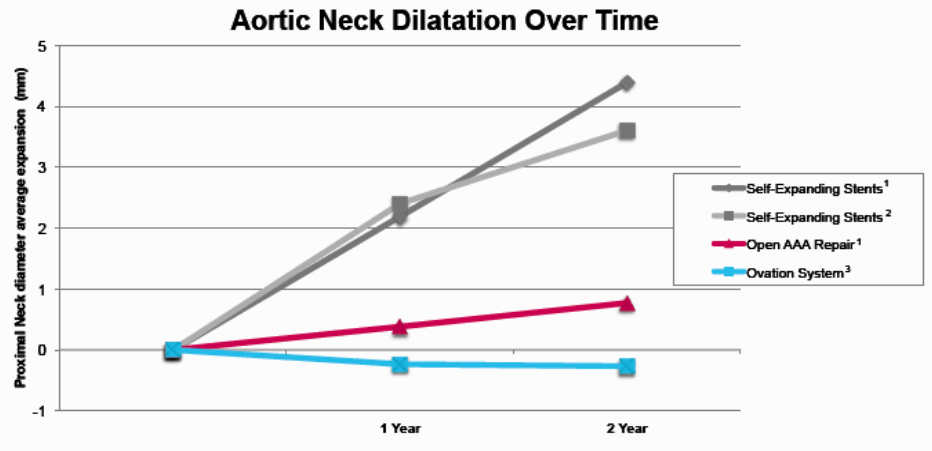


Blood Pressure
+ Stent Outward Radial Force
➡ Contributes to Neck Dilatation

Ovation Prime Stent Graft
Polymer-filled O-ring insulates aortic neck from blood pressure

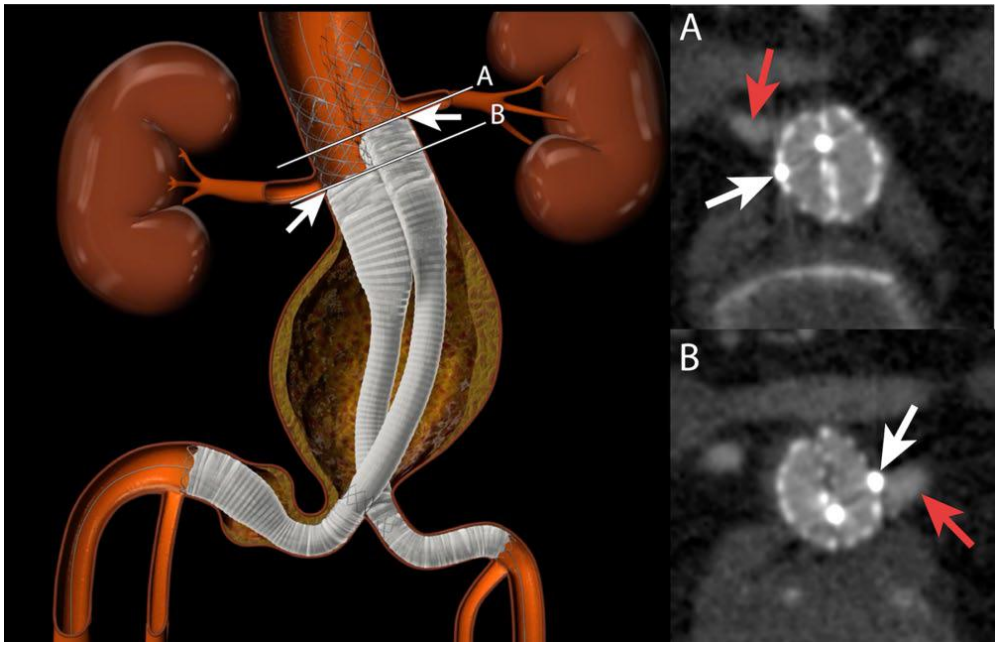


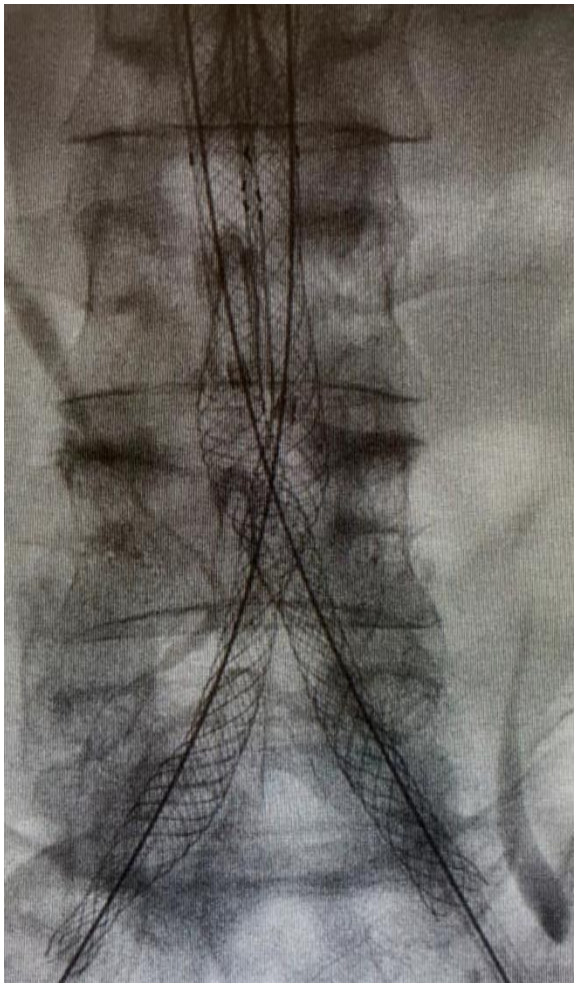
Minimal Blood Pressure
+ NO Stent Outward Radial Force
➡ No Neck Dilatation

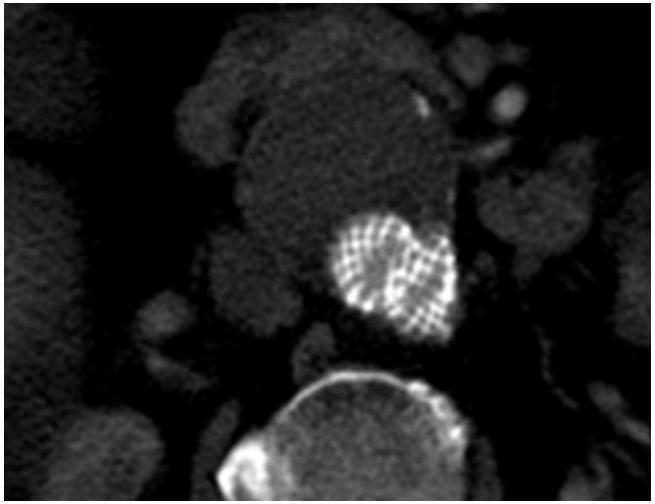


Ανάπτυξη Nitinol-free πρόσφυσης (Ovation)

Ιδανικά σε οριακούς αυχένες (πχ. κοντούς ή ευρείς ≤30mm) ?





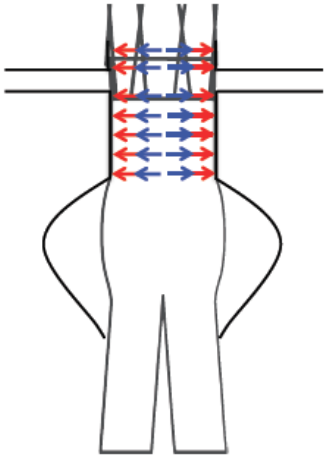


Πλεκτός σκελετός Nitinol – NO MAIN BODY!!
(Altura - Lombard)

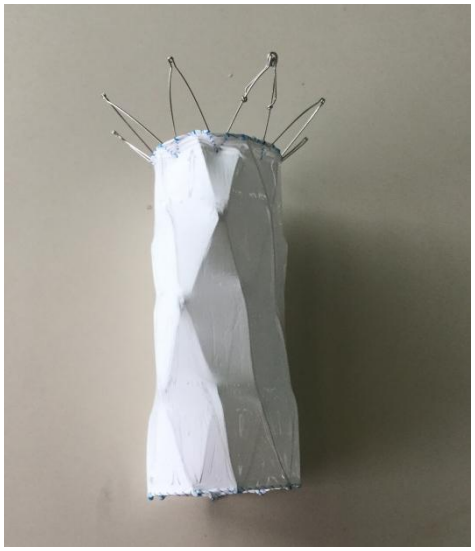
Chromium-cobalt ενδοσκελετός σε AFX

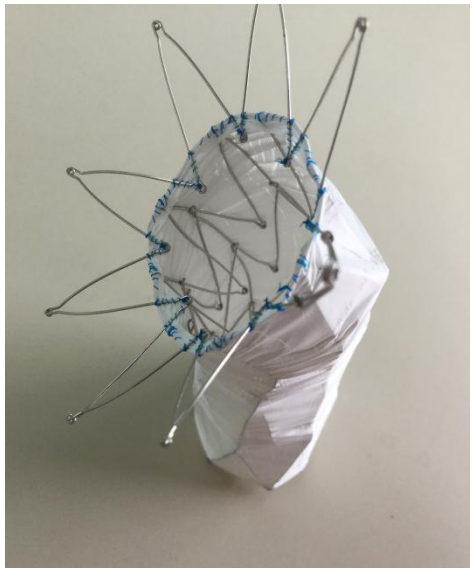
Self Expanding Stent Graft

Oversized wire and fabric graft allows transmission of blood pressure, and exerts pressure of its own

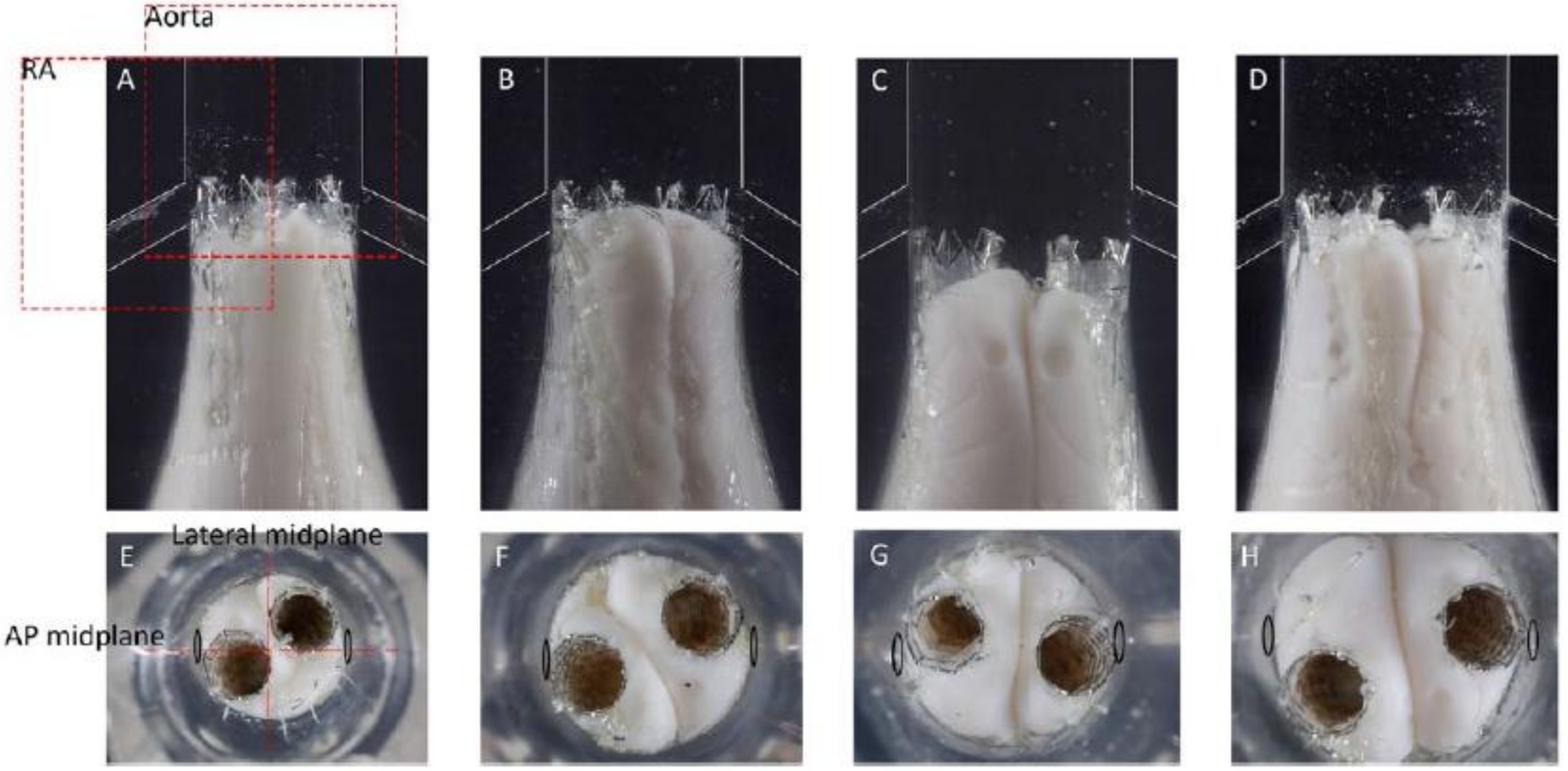


Blood Pressure
+ Stent Outward Radial Force
➡ Contributes to Neck Dilatation





Σύστημα ενδοσφράγισης σε Nellix
No Main-body!



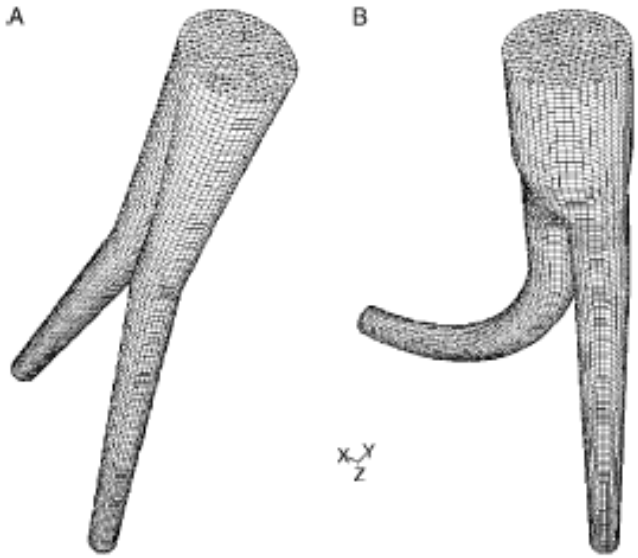
(Boersen et al., JEVT 2017; 24:677-87)

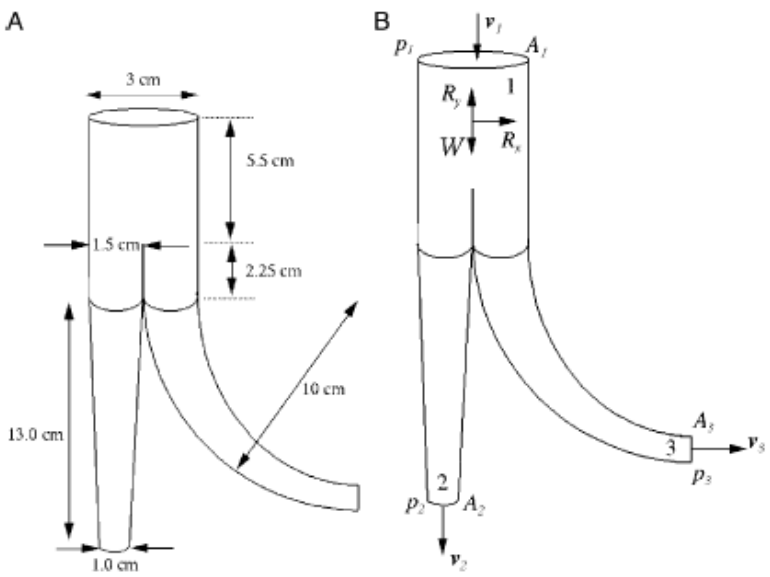
ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

ΛΑΓΟΝΙΑ ΣΚΕΛΗ

- ✓ΠΕΡΙΦΕΡΙΚΗ ΠΡΟΣΦΥΣΗ
- ✓ΚΑΤΑΝΟΜΗ ΔΥΝΑΜΕΩΝ
- ✓ΜΗΧΑΝΙΣΜΟΙ
- ✓ΕΝΔΟΔΙΑΦΥΓΕΣ
- ✓Ο ΡΟΛΟΣ & Η ΣΥΣΧΕΤΙΣΗ ΤΗς ΓΕΩΜΕΤΡΙΑΣ
- ✓ΒΕΛΤΙΩΣΕΙΣ & ΤΡΟΠΟΠΟΙΗΣΕΙΣ

(!) Η καμπυλότητα των λαγονίων δημιουργεί επιπρόσθετες δυνάμεις μετανάστευσης στα άκρα





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

ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

Displacement Forces in Iliac Landing Zones and Stent Graft Interconnections in Endovascular Aortic Repair: An Experimental Study

H. Roos [a,*], M. Ghaffari [a], M. Falkenberg [b], V. Chernoray [c], A. Jeppsson [a,d], H. Nilsson [c]

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ
DEMOCRITUS UNIVERSITY OF THRACE

What about iliacs??

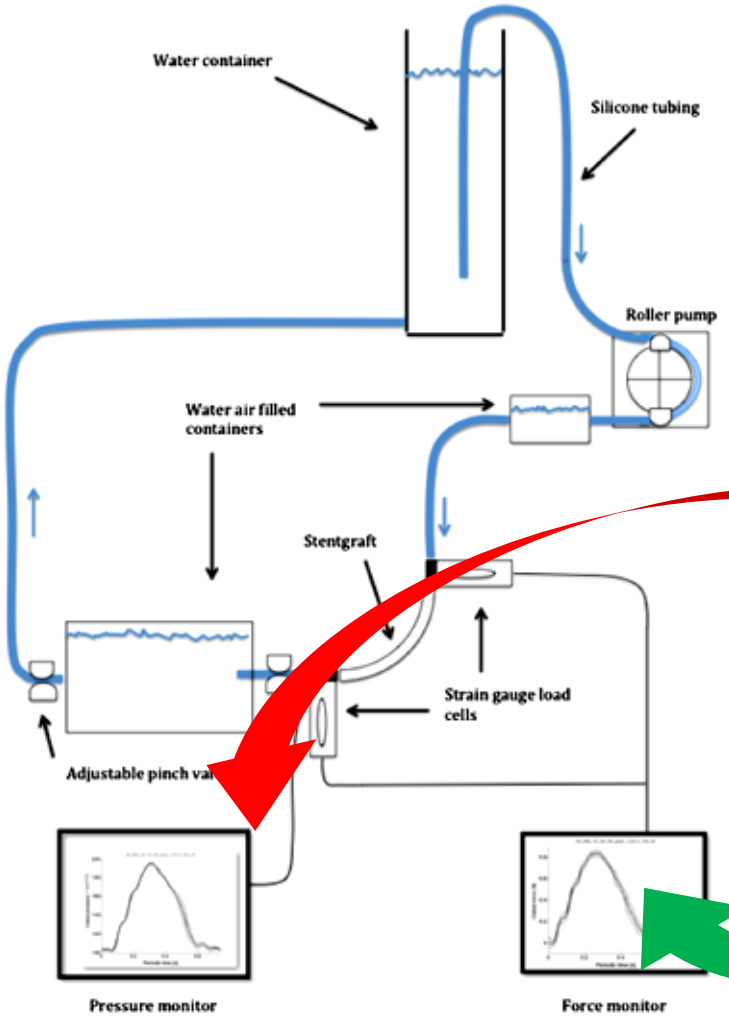


Figure 1. Perfusion model.

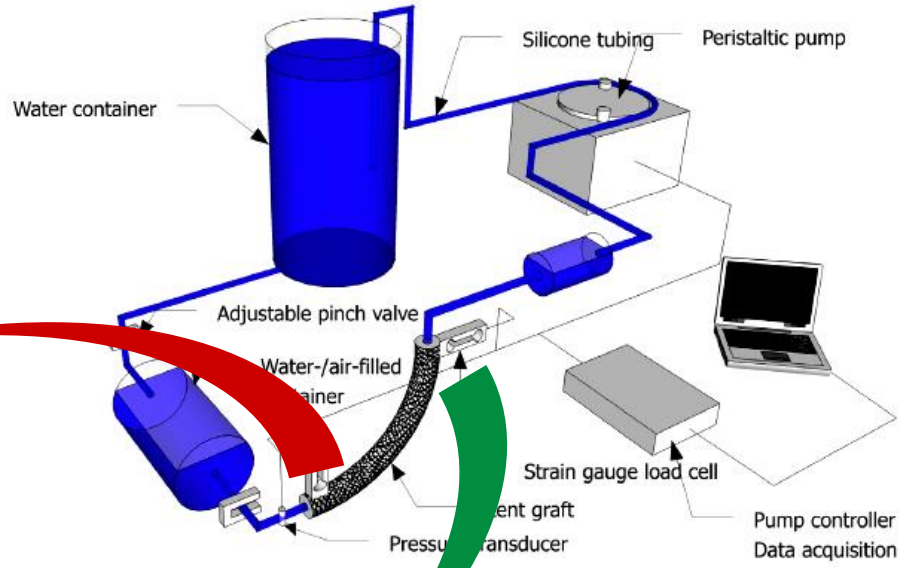


Figure 1. Schematic presentat of the aortic perfusion model.

Eur J Vasc Endovasc Surg (2016) 52, 150–156

Displacement Forces in Stent Grafts: Influence of Diameter Variation and Curvature Asymmetry

H. Roos [a,*], M. Tokarev [b], V. Chernoray [b], M. Ghaffari [d], M. Falkenberg [c], A. Jeppsson [d,e], H. Nilsson [b]

What about iliacs??

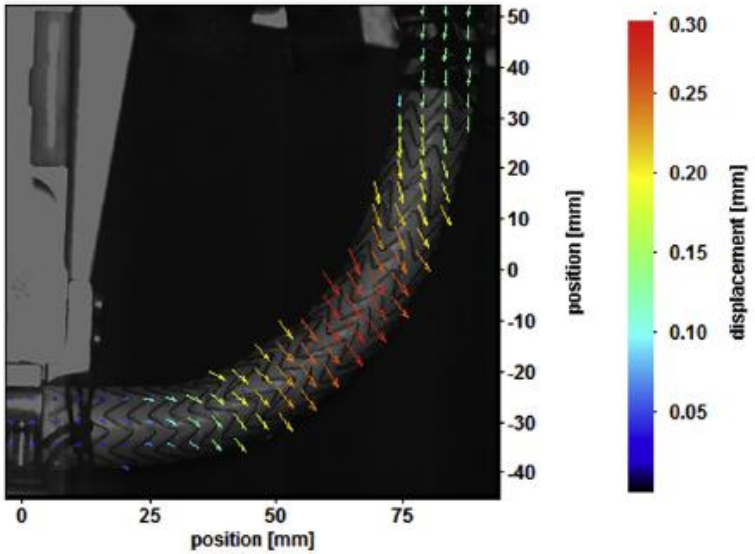
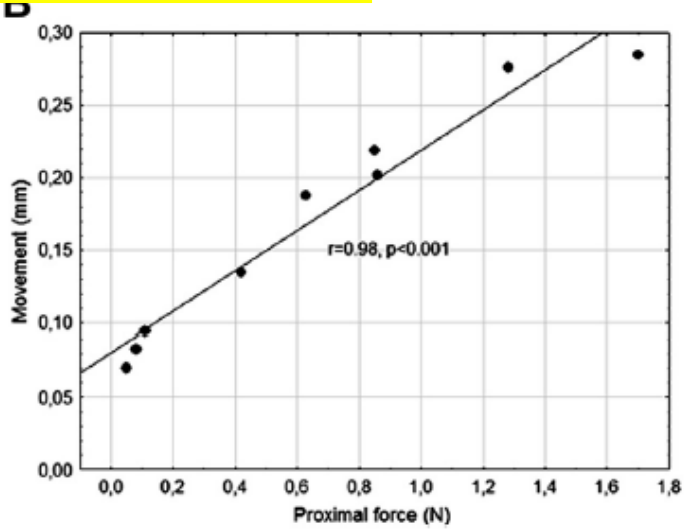
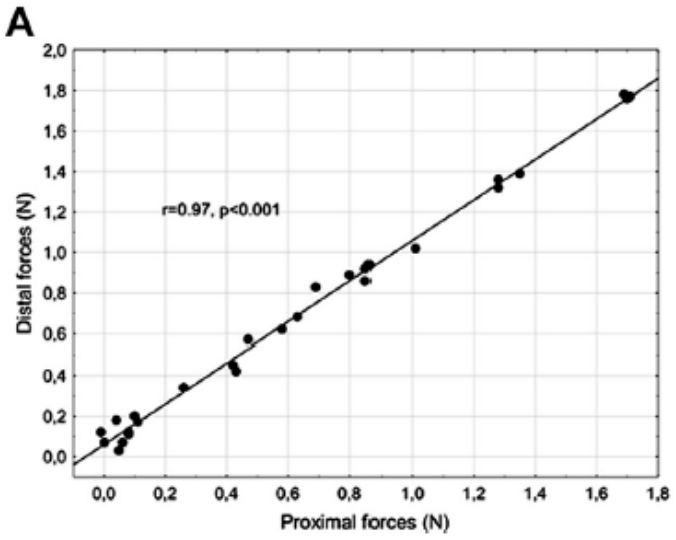


Figure 5. Sideways movement of the stent graft at 195/100 perfusion pressure and 90° angle.



Δυνάμεις συγκρίσιμες του υπολοίπου ενδομοσχεύματος αν η γωνίωση είναι μεγάλη!!



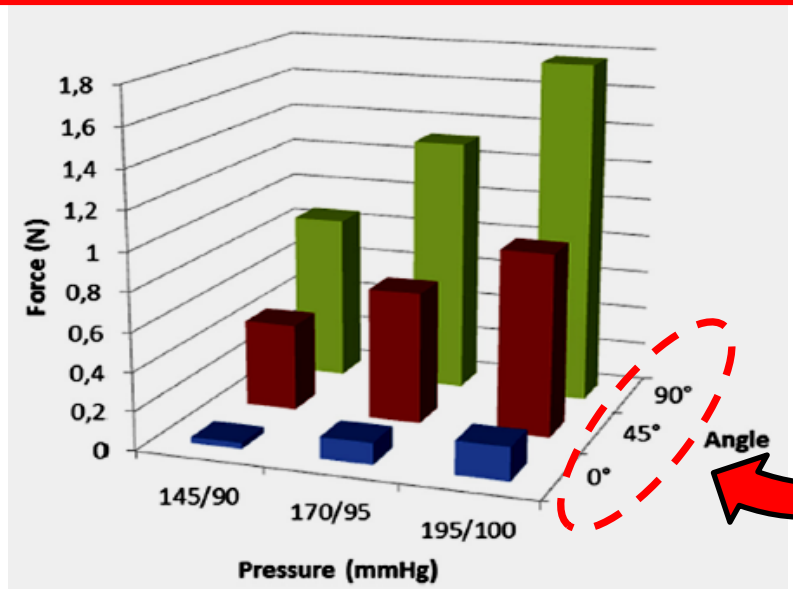
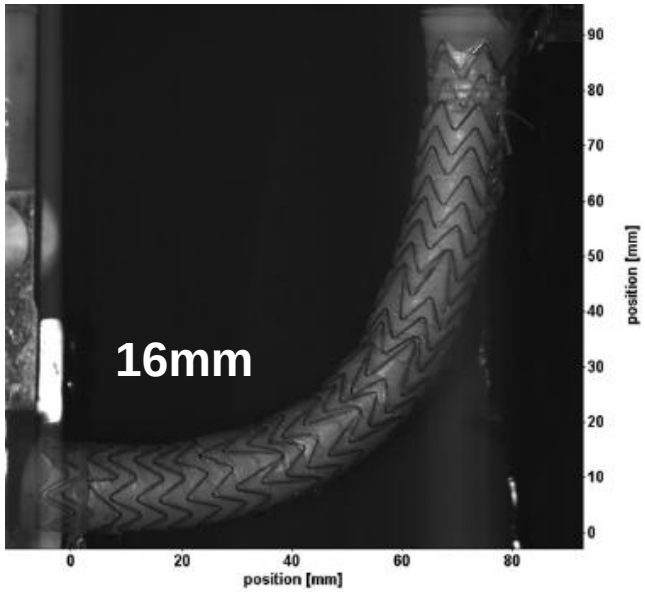
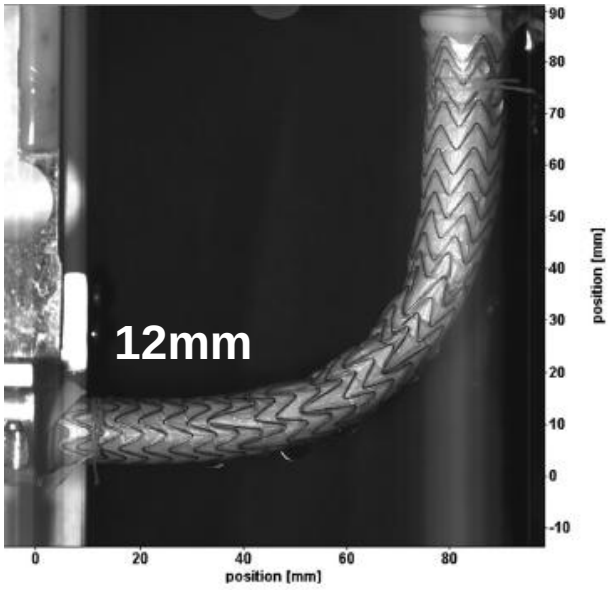


Figure 3. Peak force at the distal strain gauge cell at 80 b.p.m. at different perfusion pressures and stent graft angles.

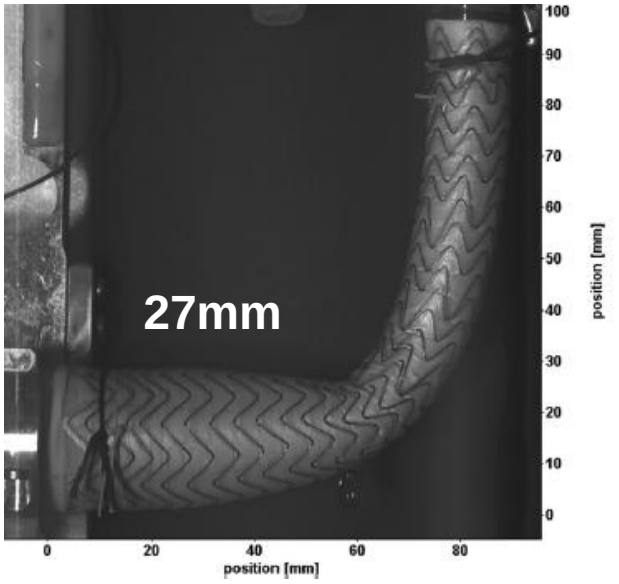
What about iliacs??



tapered



Bell-bottom



Όσο μεγαλύτερη περιφερική διάμετρος τόσο μεγαλύτερες δυνάμεις στα λαγόνια σκέλη!

Flow induced displacement forces were assessed in an experimental model in EVAR iliac stent grafts in relation to distal diameter and asymmetric stent graft curvatures. Forces were particularly high at the distal end of bell-bottom grafts. Patients treated with bell-bottom grafts may require more vigilant surveillance and improved graft fixation.

What about iliacs??

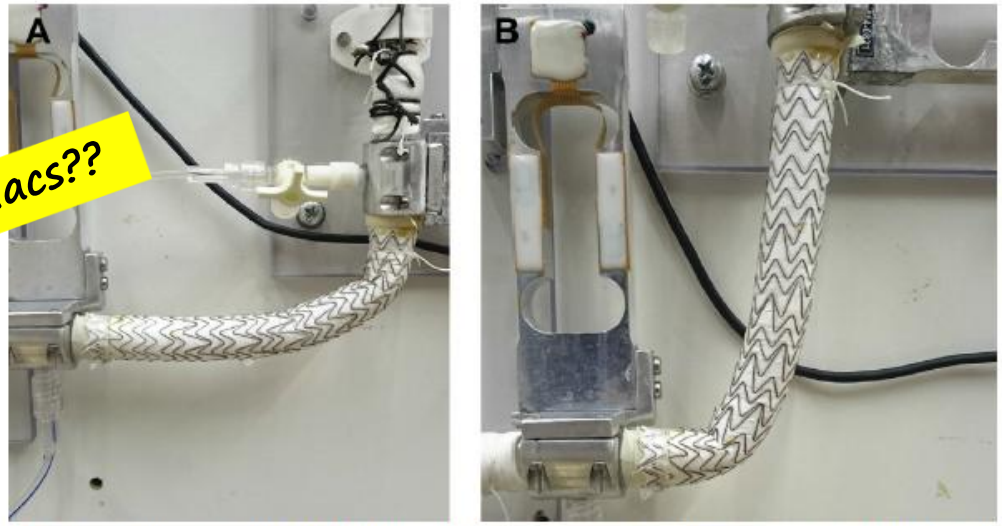


Figure 3. Stent graft with asymmetric curvature. (A) proximal length to bend—distal length, 1:3. (B) Proximal length to bend—distal length 3:1.

	Proximal end			Distal end		
Angle	0°	45°	90	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

Table 2. Flow induced displacement forces (N) in the proximal and distal end of the stent graft at asymmetric curvatures and perfusion pressures.

	Proximal					Distal				
	3:1	2:1	1:1	1:2	1:3	3:1	2:1	1:1	1:2	1:3
145/80	0.94	1.12	1.19	1.17	1.23	1.23	1.19	1.18	0.95	0.94
170/90	1.28	1.41	1.55	1.61	1.68	1.63	1.50	1.52	1.45	1.25
185/100	1.56	1.70	1.90	1.94	2.10	1.97	1.77	1.85	1.83	1.56

ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

ΛΑΓΟΝΙΑ ΣΚΕΛΗ

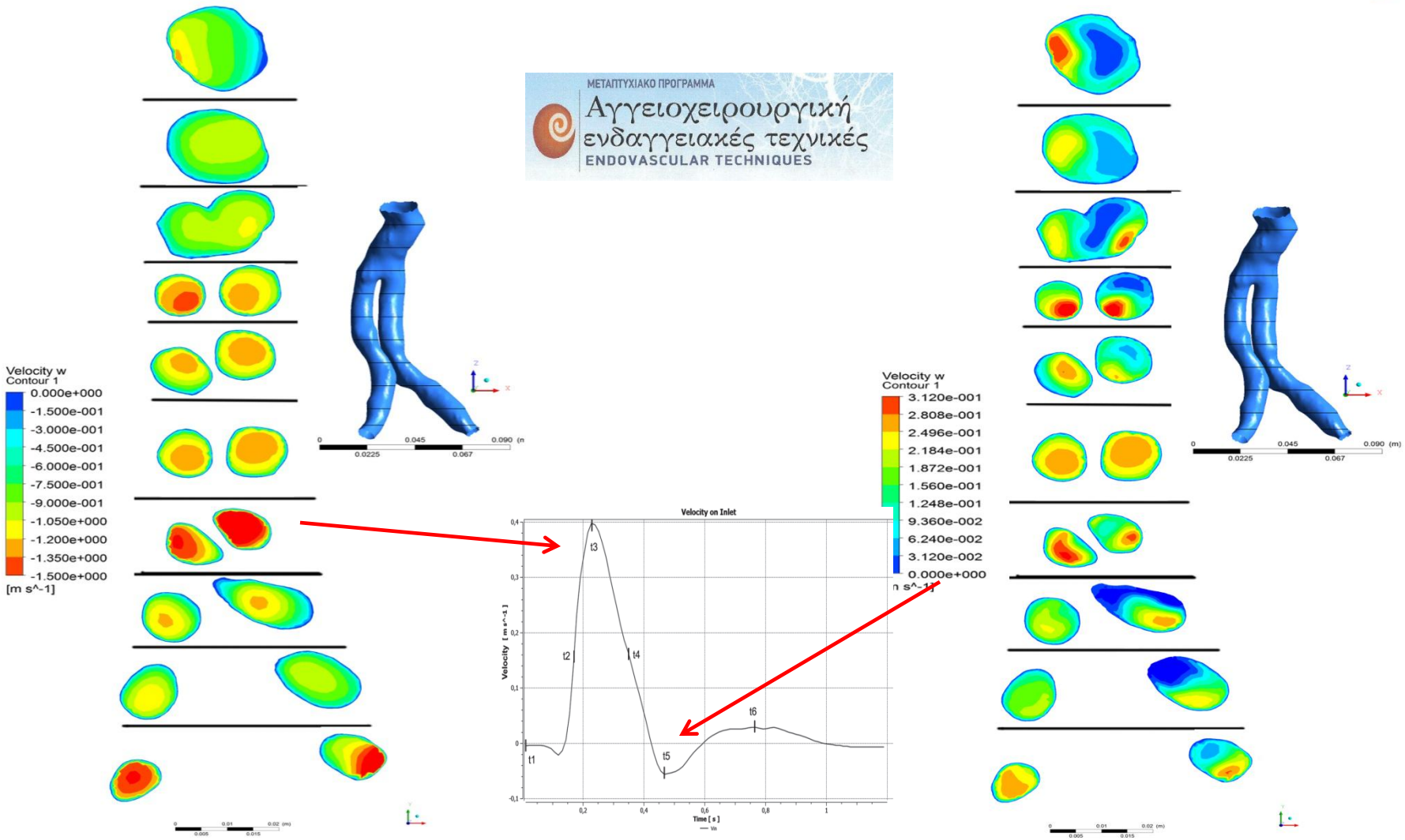
- ✓ΦΑΙΝΟΜΕΝΑ ΡΟΗΣ
- ✓ΔΙΑΤΜΗΤΙΚΕΣ ΤΑΣΕΙΣ
- ✓ΜΗΧΑΝΙΣΜΟΙ ΕΠΙΠΛΟΚΩΝ

Studying the flow dynamics in an aortic endograft with crossed-limbs

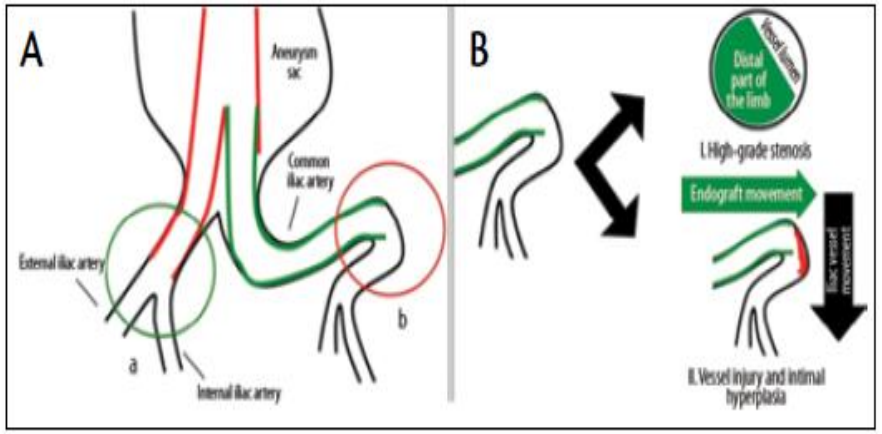
Efstratios Georgakarakos[1], Antonios Xenakis[2], Christos Manopoulos[2], George S. Georgiadis[1], Christos Argyriou[1], Sokrates Tsangaris[2], Miltos K. Lazarides[1],

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ
DEMOCRITUS UNIVERSITY OF THRACE

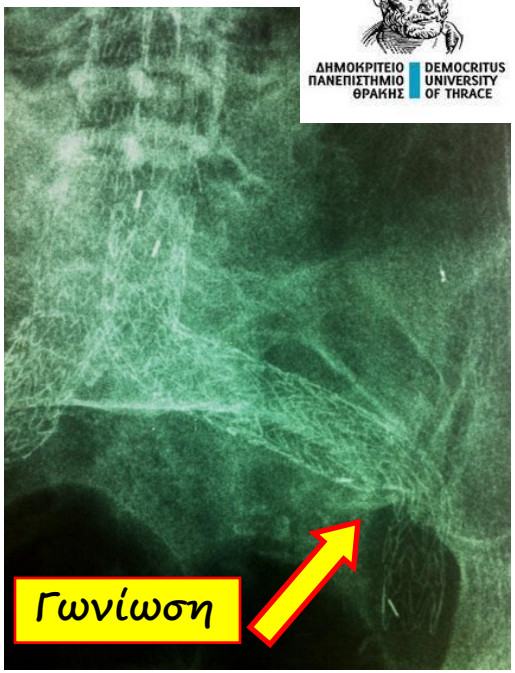
ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES



Η γεωμετρία επηρεάζει την κατανομή ταχυτήτων και διατμητικών τάσεων στα σκέλη…



Ελίκωση

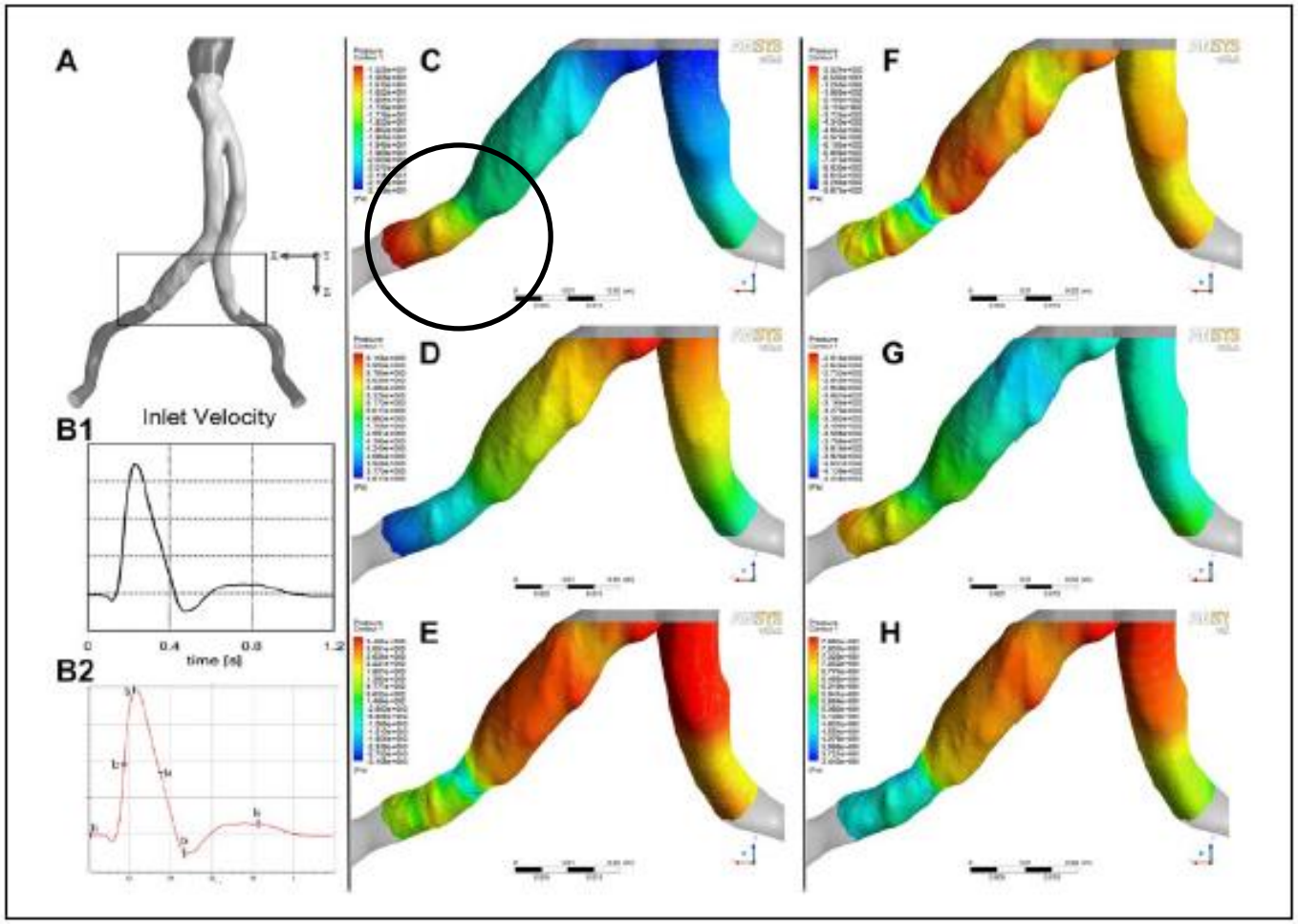


Γωνίωση

Προτεινόμενος μηχανισμός επίδρασης της ελίκωσης λαγονίων

Μη ιδανική απόθεση του περιφερικού άκρου του stent σε ελικωμένο αγγείο οδηγεί σε τραυματισμούς του ενδοθηλίου λόγω διαφορετικής κινητικότητας του stent και του αγγείου κατά τη διάρκεια του καρδιακού κύκλου ⇒ Μυοενδοθηλιακή υπερπλασία ⇒ Στένωση ⇒ Απόφραξη

Georgakarakos et al, JVET 2015



Η στένωση στα λαγόνια σκέλη προκαλεί μεταβολές στην κατανομή πιέσεων και διατμητικών τάσεων προδιαθέτοντας σε απόφραξη…

Georgakarakos et al, JVET 2015

Συμπεράσματα-Ι

Σύνοψη της επίδρασης των γεωμετρικών παραγόντων στα ενδομοσχεύματα

Geometrical Factors Influencing the Hemodynamic Behavior of the AAA Stent Grafts: Essentials for the Clinician

Efstratios Georgakarakos · Christos Argyriou · Nikolaos Schoretsanitis · Chris V. Ioannou · Nikolaos Kontopodis · Robert Morgan · Dimitrios Tsetis

Table 1 The influence of geometric factors of endografts on displacement forces

	Total forces	Forces on iliacs	Forces on bifurcation
Inlet (neck) diameter	+++	++	++
Neck angulation	++*	+	+
Endograft curvature	++	++	++
Iliac limbs bifurcation angle	+	+	+
Inlet to outlet diameter ratio	+++	++	++
Main body-limbs length ratio	+	+++	++

Cardiovasc Intervent Radiol. 2014;37(6):1420-9.

Συμπεράσματα-Ι

1. CFD: χρήσιμα δεδομένα για την κατανόηση των παθοφυσιολογικών στοιχείων & αποσαφήνιση της συμπεριφοράς των ενδομοσχευμάτων

2. Ο συνδυασμός των γεωμετρικών στοιχείων είναι χρησιμότερος από τη μελέτη μεμονωμένων παραμέτρων

3. Κανένα μόσχευμα δεν είναι ιδανικό; Κάθε ΑΚΑ έχει μοναδική ανατομία που εξυπηρετείται καλύτερα από συγκεκριμένα ενδομοσχεύματα παρά από κάποια άλλα

4. Η αιμοδυναμική θεώρηση μπορεί να βοηθήσει στη βελτίωση των χαρακτηριστικών των stent για καλύτερα κλινικά αποτελέσματα

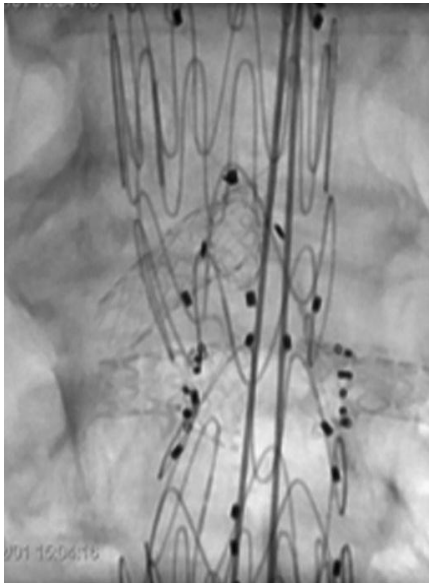
5. Οι κλινικές μελέτες είναι απαραίτητες για την πιστοποίηση και επαλήθευση των εργαστηριακών συμπερασμάτων

ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

CURRENT HOT ISSUES

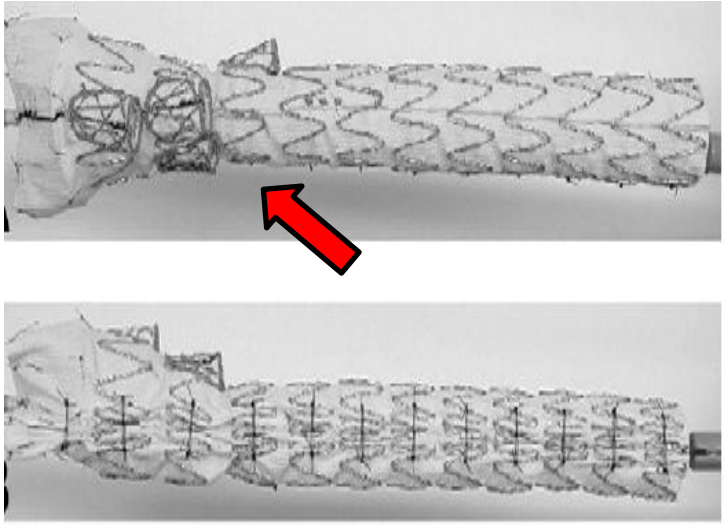
- ✓ΕΞΩΘΡΙΚΟΙ ΥΠΟΝΕΦΡΙΚΟΙ ΑΥΧΕΝΕΣ: FEVAR, CHEVAR ή ΝΕΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΑ ?
- ✓ΣΥΜΜΕΤΟΧΗ ΛΑΓΟΝΙΩΝ ΑΝΕΥΡΥΣΜΑΤΩΝ: IBD ή BELL-BOTTOM TECHNIQUE?
- ✓FAILING EVAR: COMPLICATED ή CUSTOM-MADE ΛΥΣΕΙΣ ?

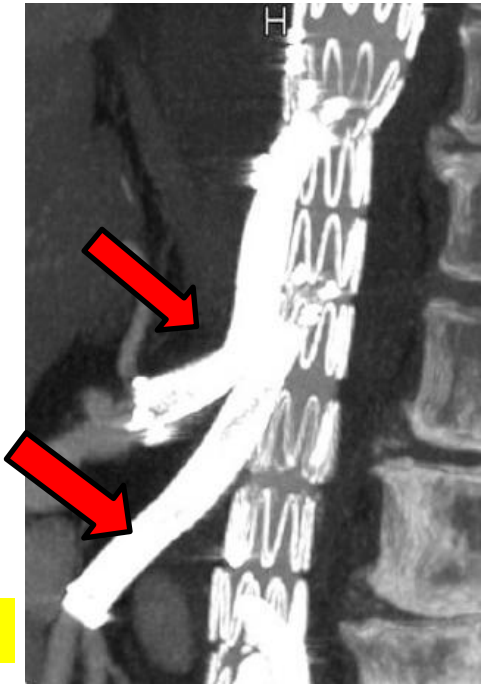
Μελέτη σύνθετων μοσχευμάτων (FEVAR)



Management of Complex Aneurysms involves:

- Fenestrations, stent-grafts, branches





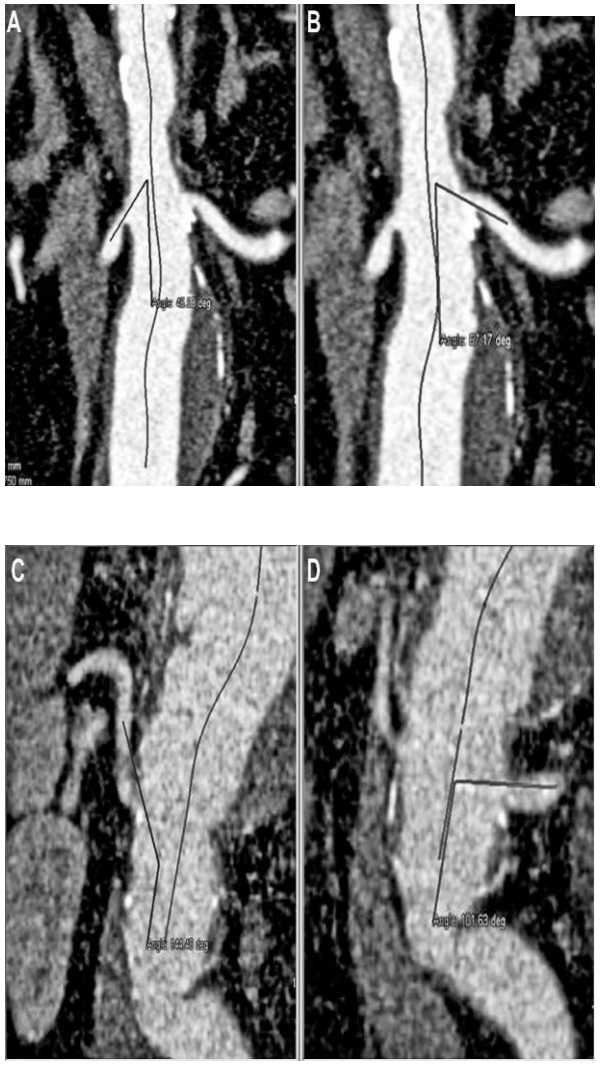
Resch et al, EJVES, 2012

Μελέτη σύνθετων μοσχευμάτων (FEVAR)

Αποκλίσεις από τον αρχικό σχεδιασμό εξαιτίας:

Διάφορες θέσεις των νεφρικών αρτηριών

- κάτωθεν για Θωρακοκοιλιακά IV
- άνωθεν για θωρακοκοιλιακά II & III



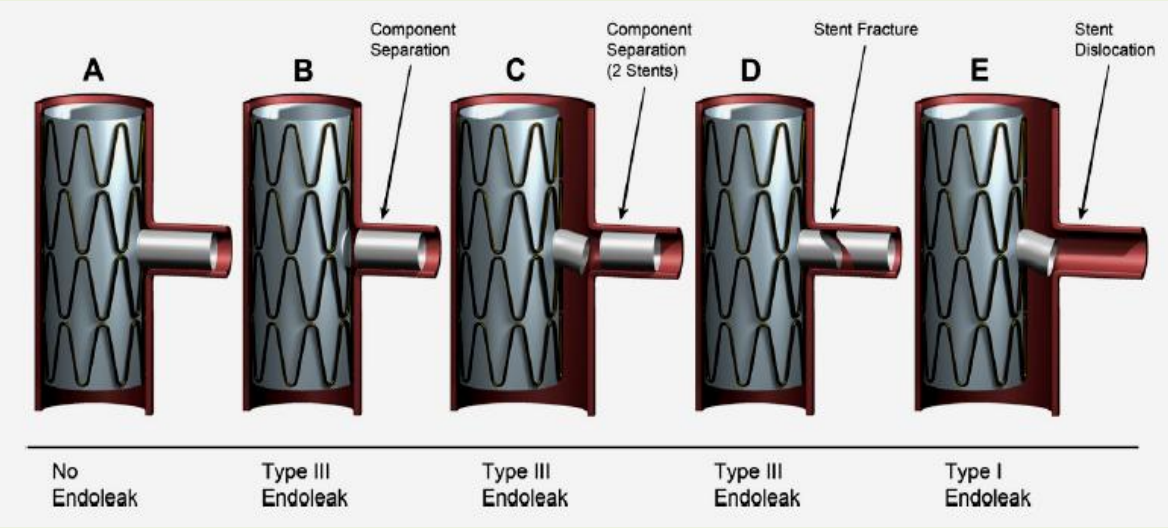
Conway et al, J Endovasc Ther, 2010

Μελέτη σύνθετων μοσχευμάτων (FEVAR)

Αποκλίσεις από τον αρχικό σχεδιασμό εξαιτίας:

Μεταβολές κατά το remodelling

- ✓ Μετανάστευση
- ✓ Γωνίωση
- ✓ Ενδοδιαφυγές



Συνεχιζόμενη κίνηση των νεφρικών αρτηριών

- ✓ Αλλαγή θέσης των νεφρικών κλάδων και stents

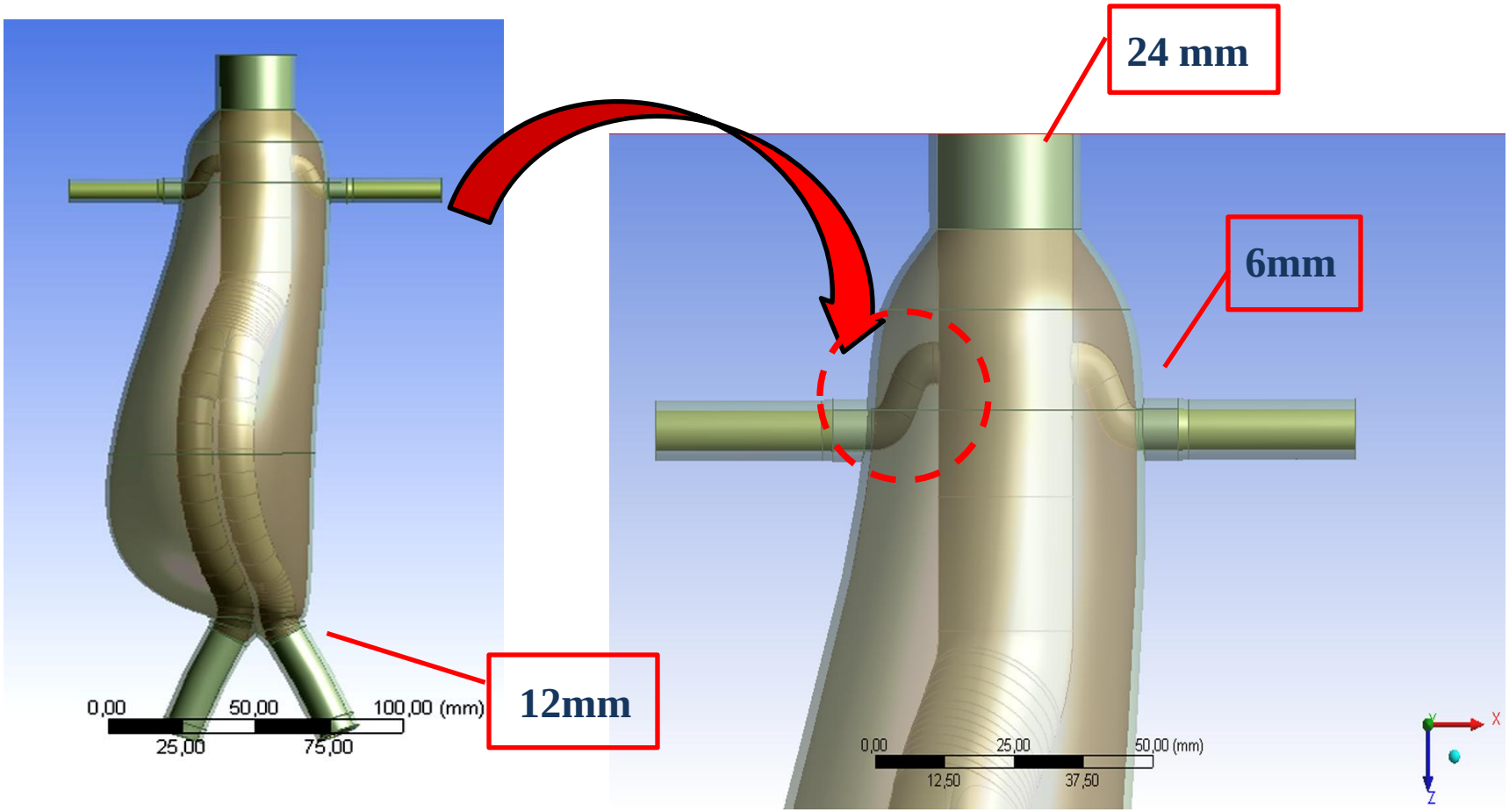
Georgakarakos et al, Vasc Med 2012
Mastracci et al, J Vasc Surg, 2013

Μελέτη σύνθετων μοσχευμάτων (FEVAR)

ΕΡΩΤΗΜΑ:

Πώς επιδρά η γεωμετρία των νεφρικών κλάδων σε:

- ✓Δυνάμεις μετανάστευσης
- ✓Εύρος διατμητικής τάσης
- ✓Κατανομή διατμητικής τάσης

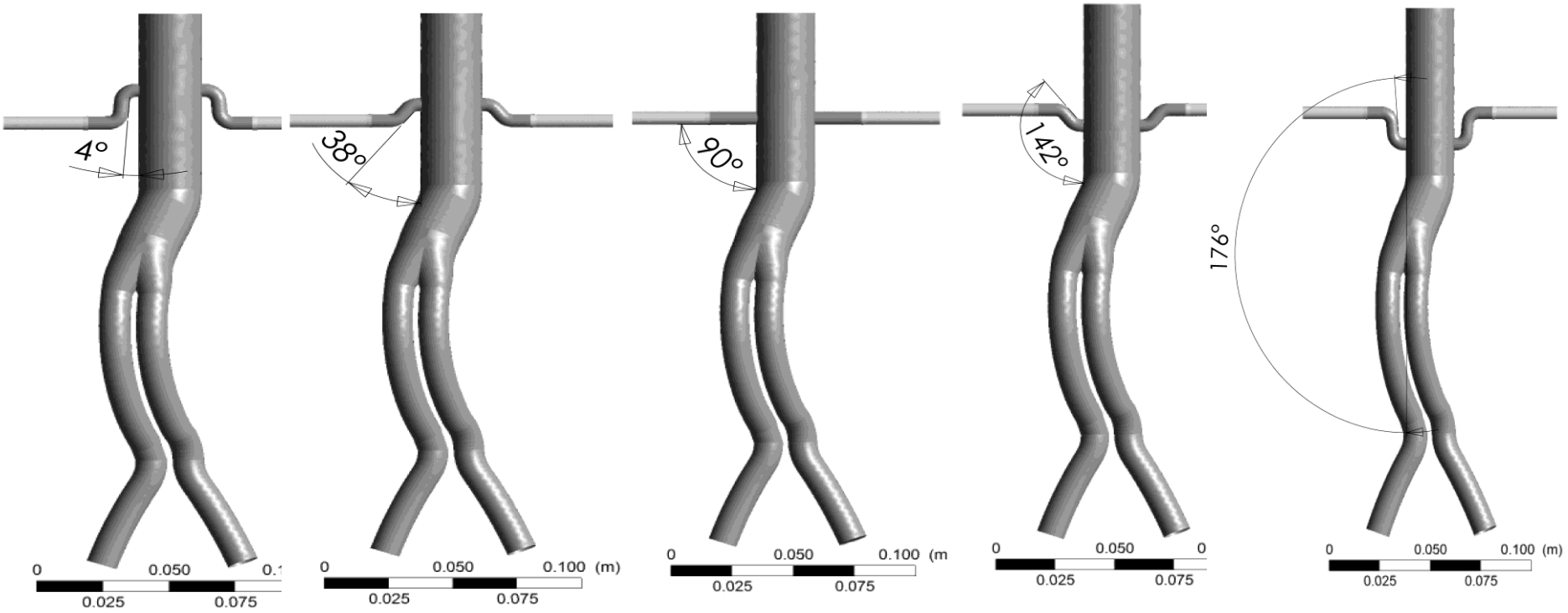


The Hemodynamic Impact of Misalignment of Fenestrated Endografts: A Computational Study☆

E. Georgakarakos [a,*], A. Xenakis [b], G.S. Georgiadis [a], C. Argyriou [a], G.A. Antoniou [c], N. Schoretsanitis [a], M.K. Lazarides [a]

European Journal of Vascular and Endovascular Surgery Volume 47 Issue 2 p. 151–159 February/2014

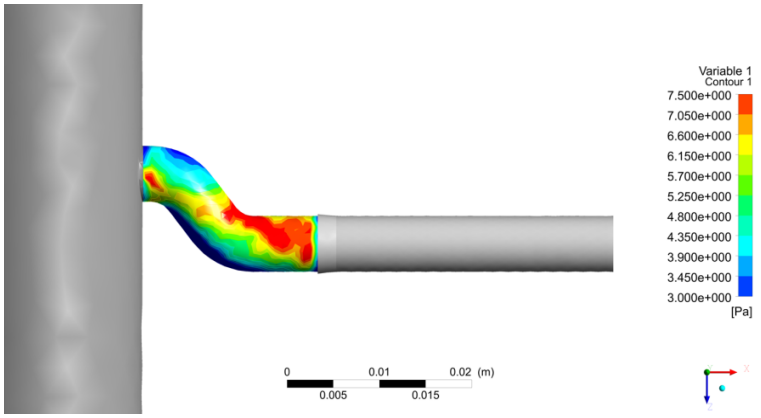
Multiple take-off angles

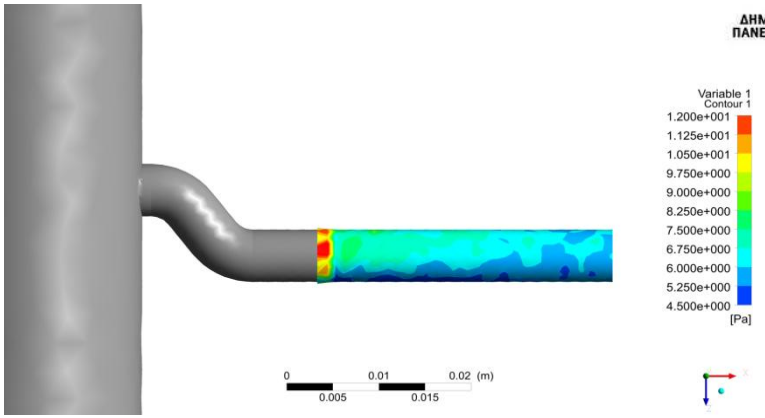


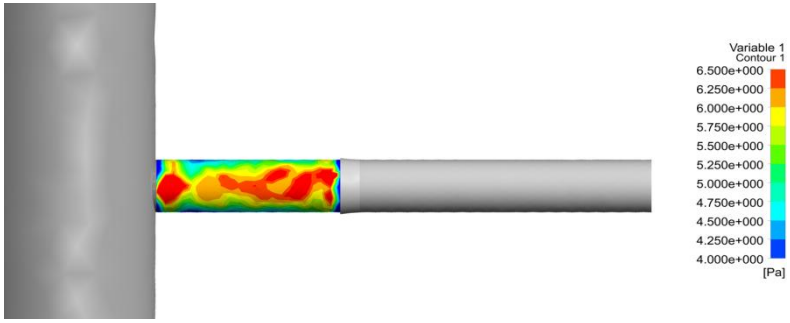
ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
Αγγειοχειρουργική ενδαγγειακές τεχνικές
ENDOVASCULAR TECHNIQUES

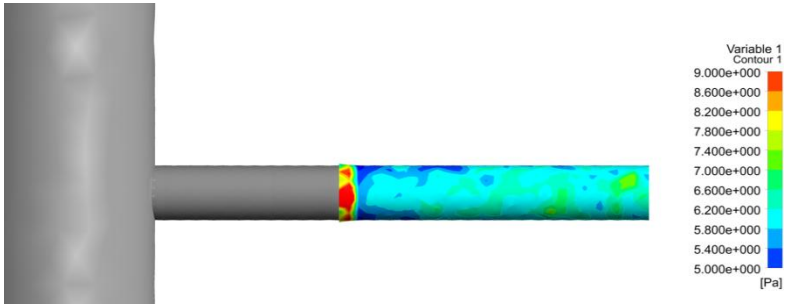
Azzaoui et al, Ann Vasc Surg 2011
Conway et al, J Endovasc Ther, 2010

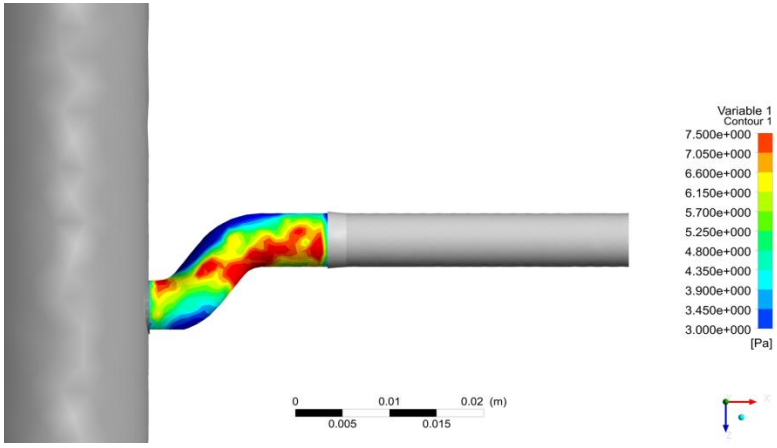
Εκτίμηση της διατμητικής τάσης

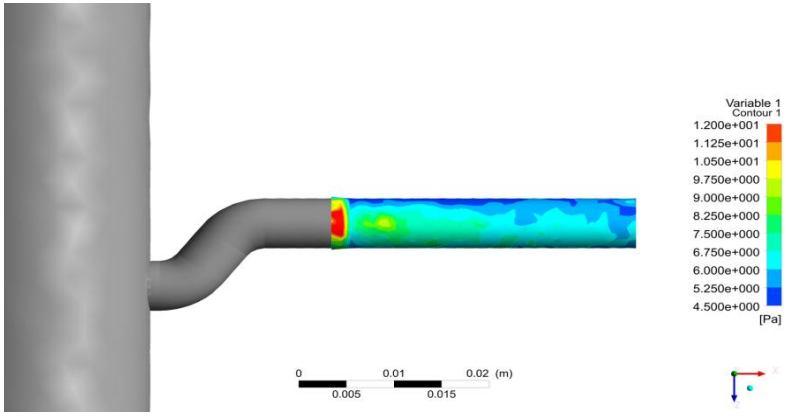




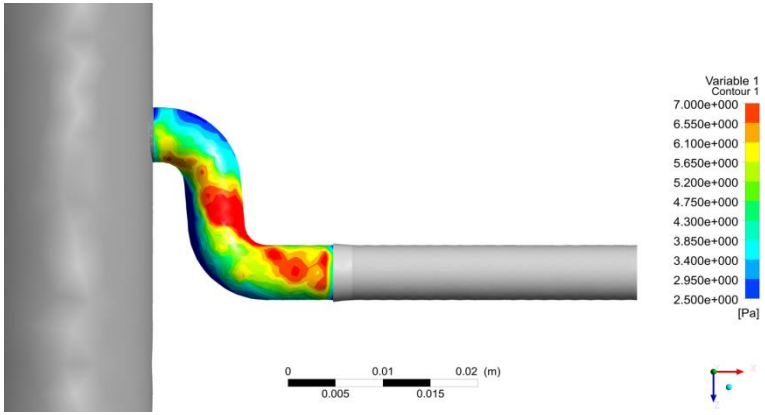


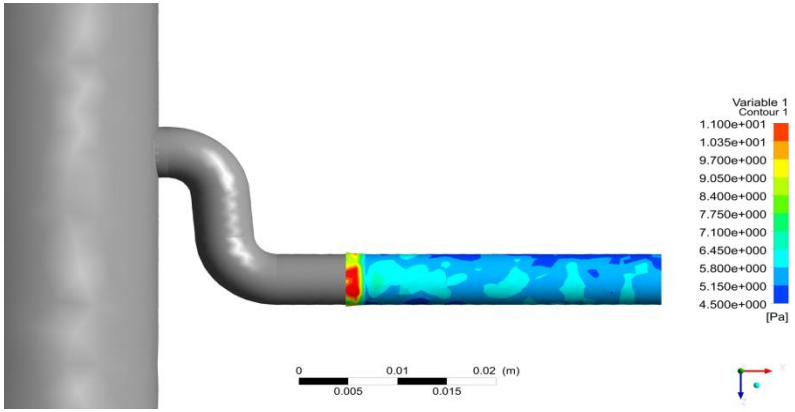


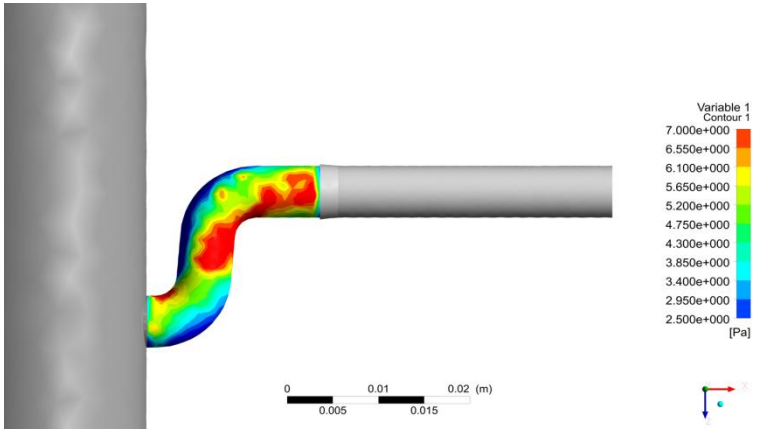


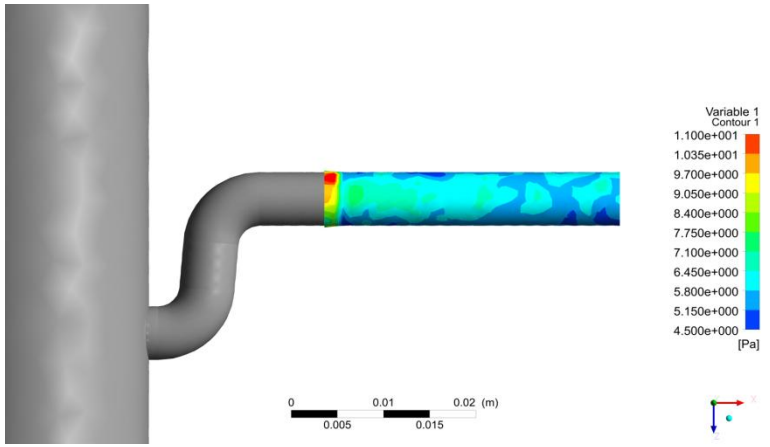


Εκτίμηση της διατμητικής τάσης



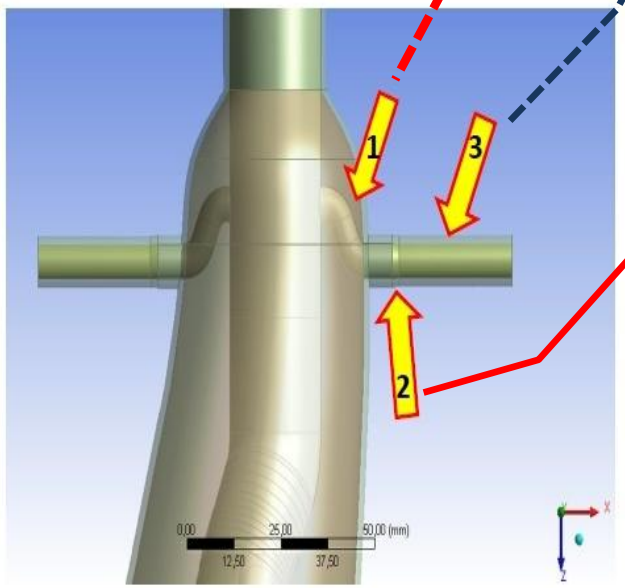




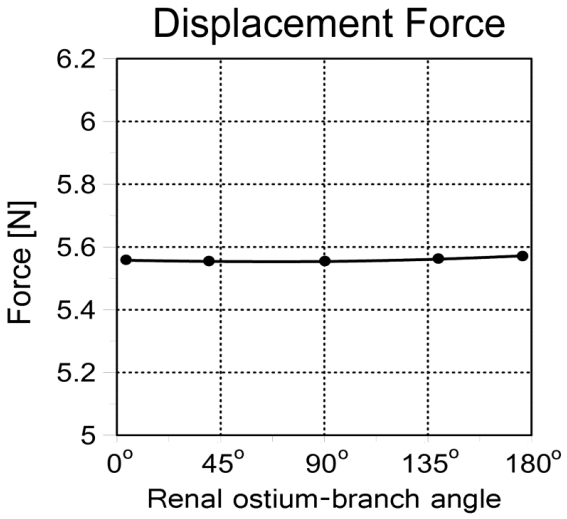


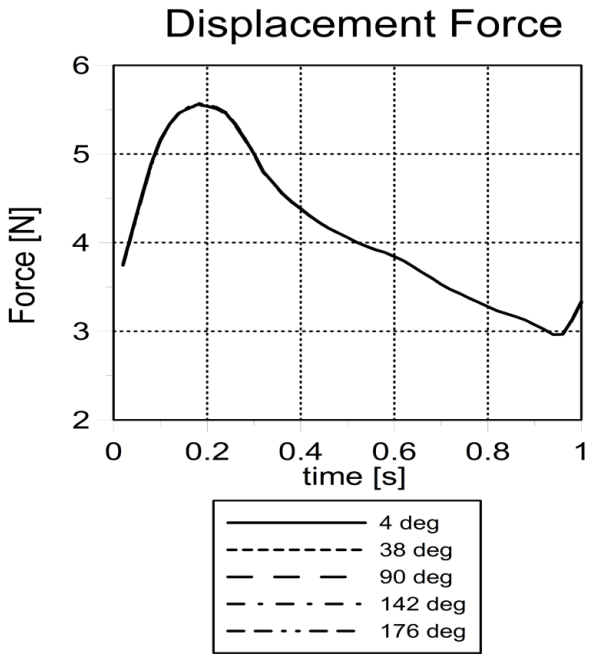
Εκτίμηση της διατμητικής τάσης

Shear stress (Pa)				
Take-off angle	Min Branch	Max Branch	Post-mating renal	Transition zone
4°	0,139	10,986	1,938	14,09
38°	0,1	11,4	1,975	16,467
90°	2,297	8,291	2,297	12,447
142°	0,117	10,76	1,955	16,083
176°	0,01	10,258	2,238	15,336



max. stress στις ζώνες μετάπτωσης





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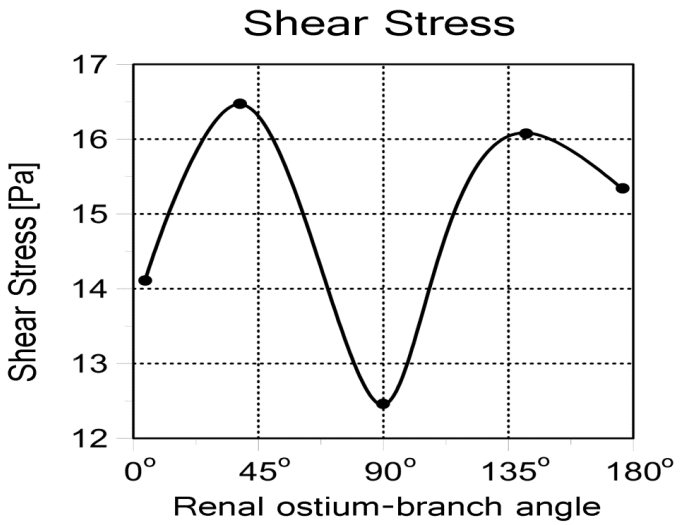
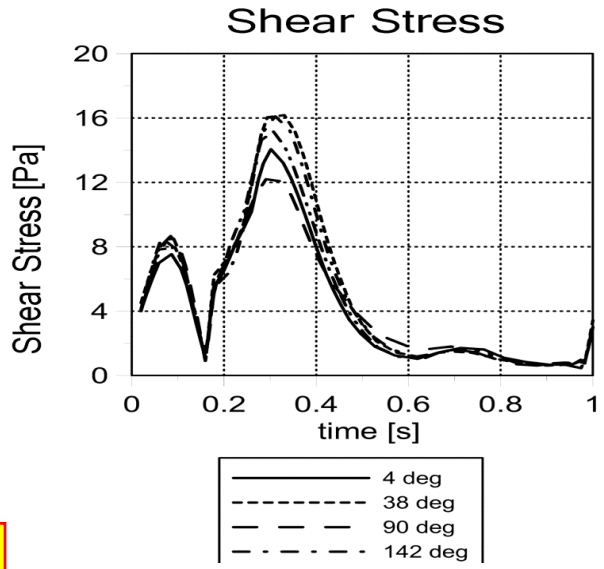
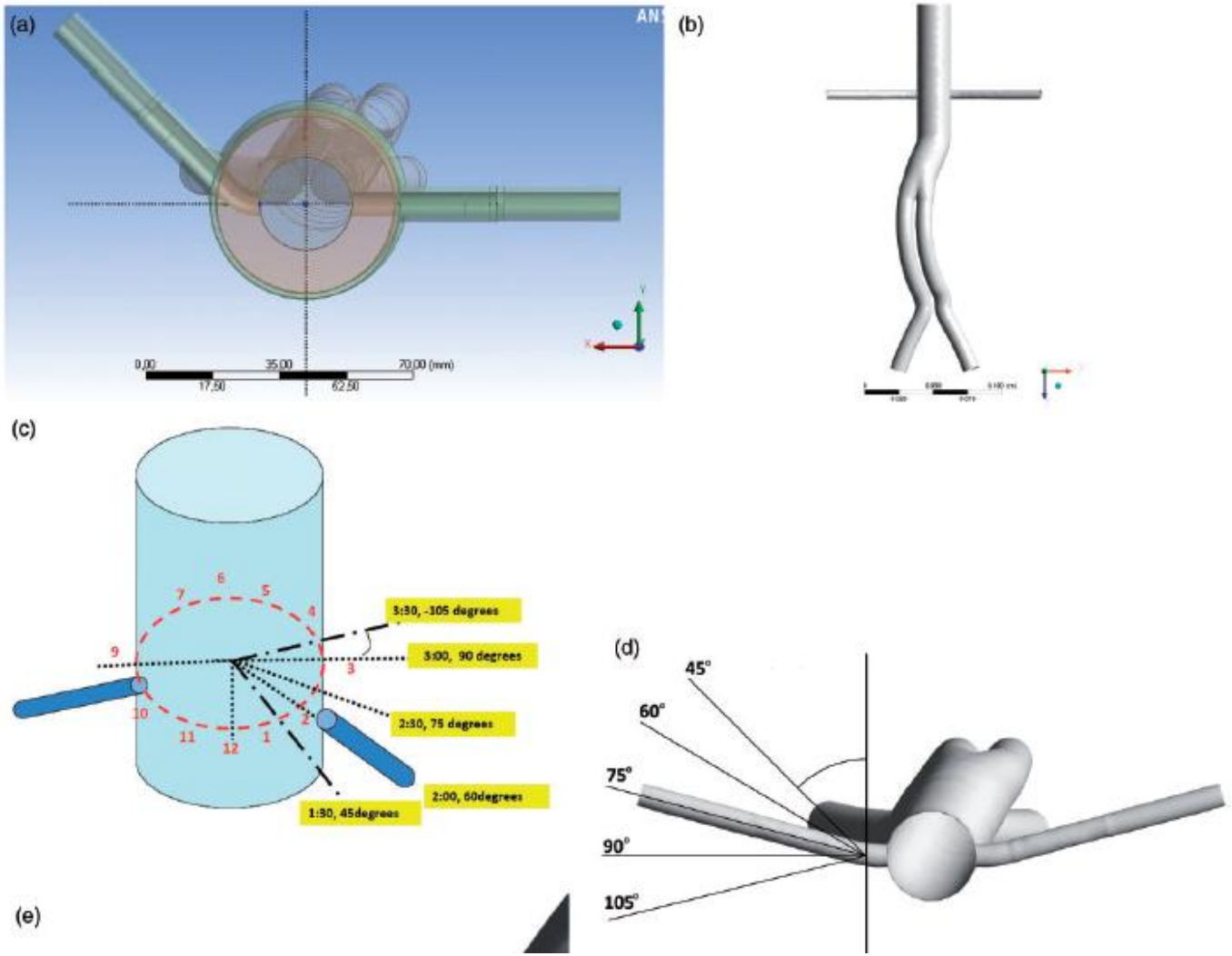
Καμία επίδραση της γωνίωσης του νεφρικού κλάδου στη μεταναστευτική δύναμη (5.5N)





Χαμηλότερη τιμή stress στις 90° (12.5 Pa)

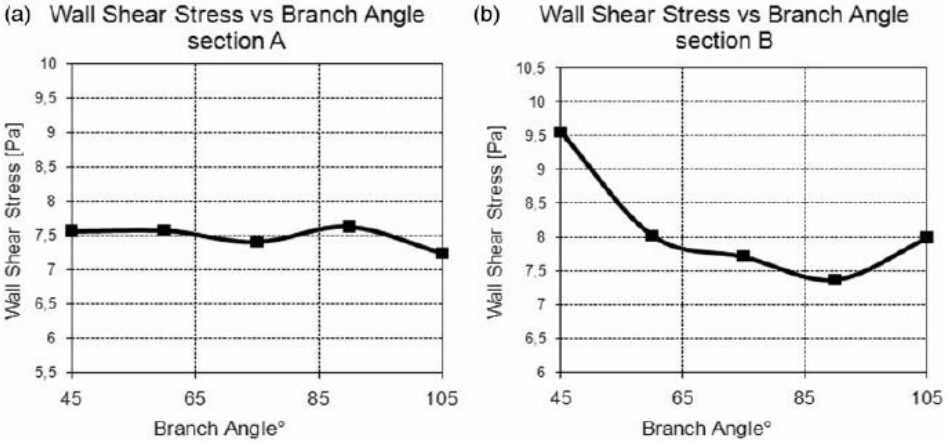
Εκτίμηση της διατμητικής τάσης σε οριζόντιες γωνίες του pFEVAR

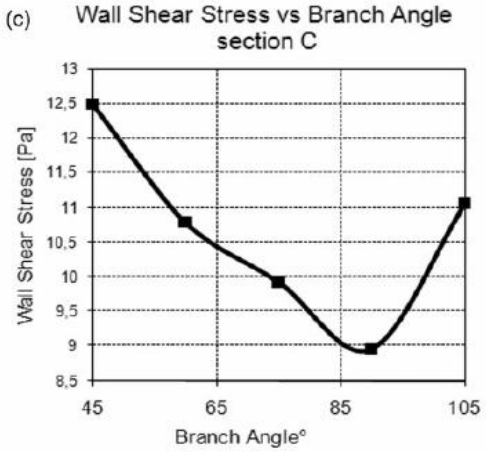


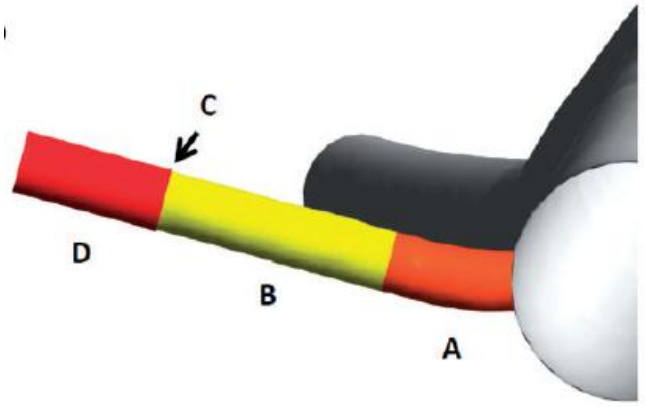
Εκτίμηση της διατμητικής τάσης στις οριζόντιες γωνίες του pFEVAR

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

Καμία επίδραση της οριζόντιας γωνίωσης στις διατμητικές τάσεις κατά μήκος του renal branch







Μέγιστη διαβάθμιση διατμητικής τάσης στη ζώνη μετάπτωσης stent-αγγείου

Original Article

Vascular

Vascular
0(0) 1–10
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DOI: 10.1177/1708538115598726
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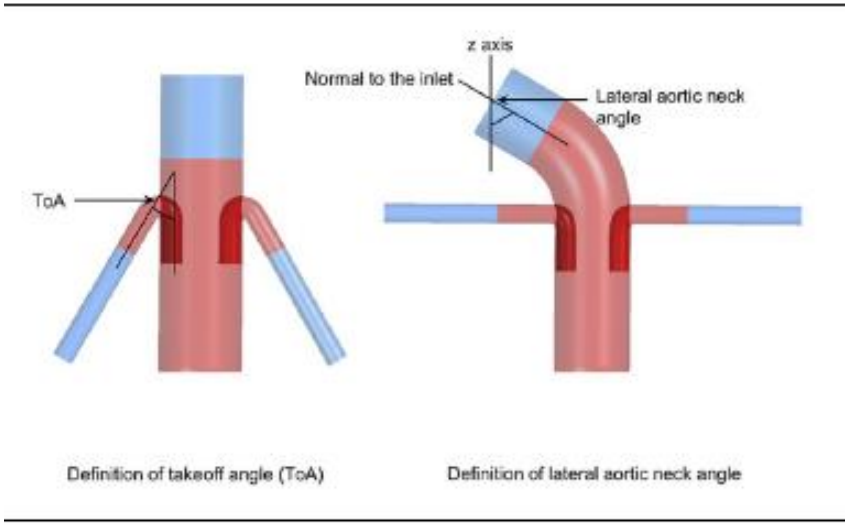
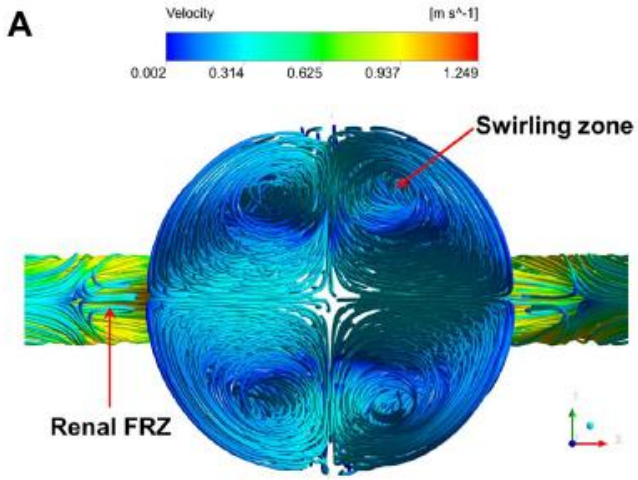
The shear stess profile of the pivotal fenestrated endograft at the level of the renal branches: A computational study for complex aortic aneurysms

Efstratios Georgakarakos[1], Antonios Xenakis[2], Theodosios Bisdas[3], George S Georgiadis[1], Nikolaos Schoretsanitis[1], George A Antoniou[4] and Miltos Lazarides[1]

Comparison of Blood Flow in Branched and Fenestrated Stent-Grafts for Endovascular Repair of Abdominal Aortic Aneurysms



Kandail et al, J Endovasc Ther 2015, 22:578-90



	Antegrade BSG	Retrograde BSG	FSG
TOA = 90° Straight neck	Outlet 1 Outlet 2 Outlet 3 Outlet 4		
TOA = 30° Straight neck			
TOA = 120° Straight neck			
TOA = 90° Angulated neck			

Comparison of Blood Flow in Branched and Fenestrated Stent-Grafts for Endovascular Repair of Abdominal Aortic Aneurysms

Table 3. Cycle-Averaged Displacement Forces Acting on All Stent-Grafts With a Straight Aortic Neck at Different Takeoff Angles and All Stent-Grafts With a Lateral Neck Angle of 60°.

	Displacement Force, N								
	Antegrade BSG			Retrograde BSG			FSG		
ToA	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
30°	1.25	0.83	1.83	1.26	0.85	1.83	1.24	0.83	1.82
90°	1.69	1.16	2.47	1.69	1.17	2.47	1.69	1.15	2.47
120°	1.95	1.35	2.83	1.95	1.36	2.83	1.95	1.35	2.84
LNA	3.65	2.69	5.27	3.65	2.70	5.26	3.64	2.69	5.26

Abbreviations: BSG, branched stent-graft; FSG, fenestrated stent-graft; LNA, lateral neck angle.

Table 1. Cycle-Averaged Flow Rate in the Renal and Iliac Arteries for All Stent-Grafts With a Straight Aortic Neck at Different Takeoff Angles.

	Mean Flow Rate, L/min					
	Renal Artery Outlet			Iliac Artery Outlet		
Stent-Graft Type	30° ToA	90° ToA	120° ToA	30° ToA	90° ToA	120° ToA
Antegrade BSG	0.53	0.54	0.53	0.51	0.50	0.51
Retrograde BSG	0.42	0.46	0.46	0.62	0.58	0.58
FSG	0.59	0.62	0.60	0.46	0.42	0.45

Abbreviations: BSG, branched stent-graft; FSG, fenestrated stent-graft; ToA, takeoff angle.

Table 2. Cycle-Averaged Flow Rate in the Renal and Iliac Arteries for All Stent-Grafts With a Lateral Aortic Neck Angulation of 60° and a Takeoff Angle of 90°.

	Mean Flow Rate, L/min			
	Renal Arteries		Iliac Arteries	
Stent-Graft Type	Outlet 1[a]	Outlet 2	Outlet 3	Outlet 4
Antegrade BSG	0.53	0.53	0.49	0.53
Retrograde BSG	0.49	0.47	0.53	0.60
FSG	0.61	0.64	0.40	0.43

Abbreviations: BSG, branched stent-graft; FSG, fenestrated stent-graft.
[a]Refer to Figure 1 for schematics of outlets 1-4.

Kandail et al, J Endovasc Ther 2015, 22:578-90

Παρόμοια αποτελέσματα με την προηγούμενη μελέτη (EJVES 2014)

Hemodynamic and Anatomic Predictors of Renovisceral Stent-Graft Occlusion Following Chimney Endovascular Repair of Juxtarenal Aortic Aneurysms

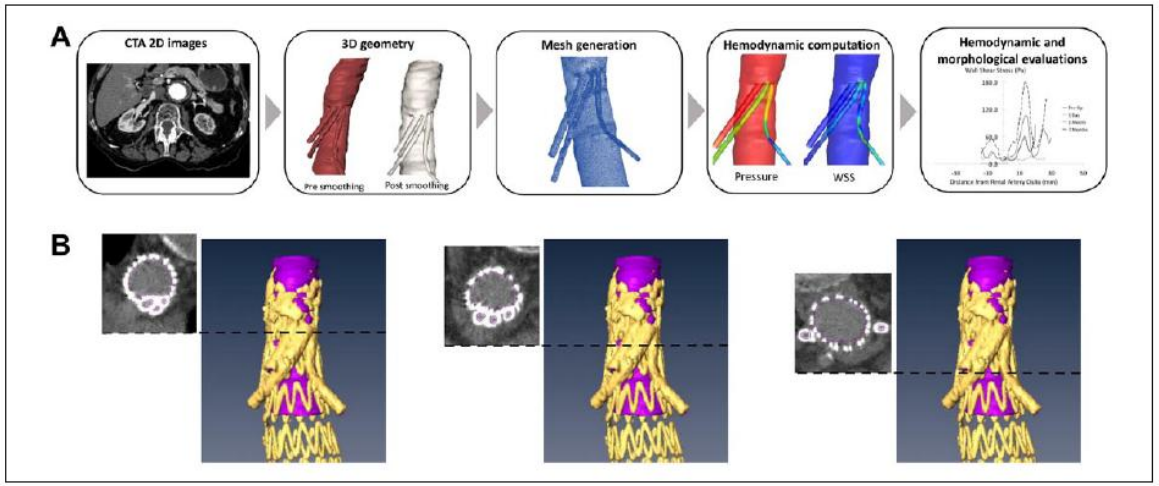
ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

Tricarico et al., JEVT; 2017, 24:880-8

Table 2. Correlation Among Anatomic and Hemodynamic Parameters Within Chimney Stent-Grafts.

	Spearman's Rank Correlation Coefficient		
	Centerline Angle	Pressure Gradient	Wall Shear Stress
Cross-sectional area	0.19	−0.08	−0.70[a]
Centerline angle	—	−0.09	−0.33[a]
Pressure gradient		—	0.13

[a]Significant at $p<0.001$.



What about chimneys?

Προσπάθεια ανάδειξης ανατομικών (cross sectional area) ή αιμοδυναμικών δεικτών (Wall Shear Stress) προγνωστικών για θρόμβωση chimneys

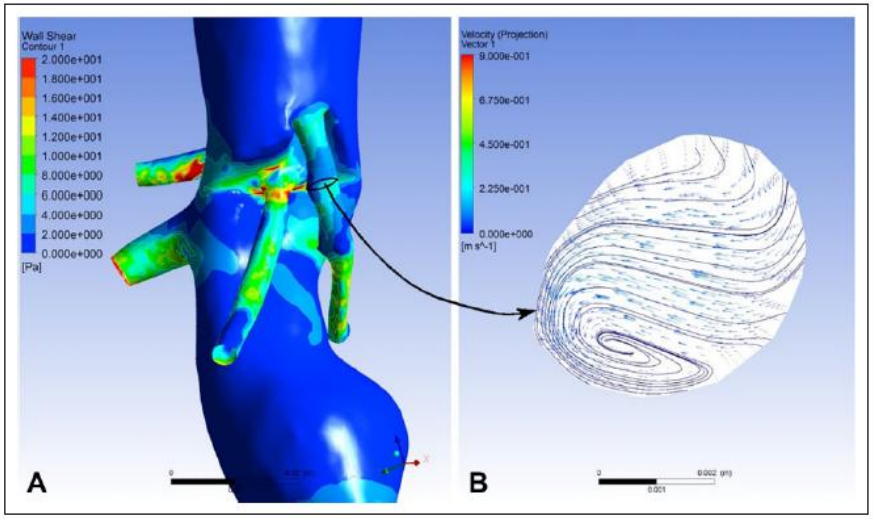
Following chEVAR, chimney stent-grafts at increased risk for occlusion demonstrated anatomic and hemodynamic signatures on the first postoperative imaging study at 1 month. A minimum CSA <14 mm^2, peak systolic pressure gradient >25 Pa/mm, and peak systolic WSS >45 Pa were associated with eventual stent-graft occlusion. It is reasonable to suggest that on reaching these thresholds, a careful evaluation of the patient's stent-graft configuration should be undertaken and the opportunities for a potential remediation procedure

Comparison of Fluid Dynamics Variations Between Chimney and Fenestrated Endografts for Pararenal Aneurysms Repair: A Patient Specific Computational Study as Motivation for Clinical Decision-Making

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

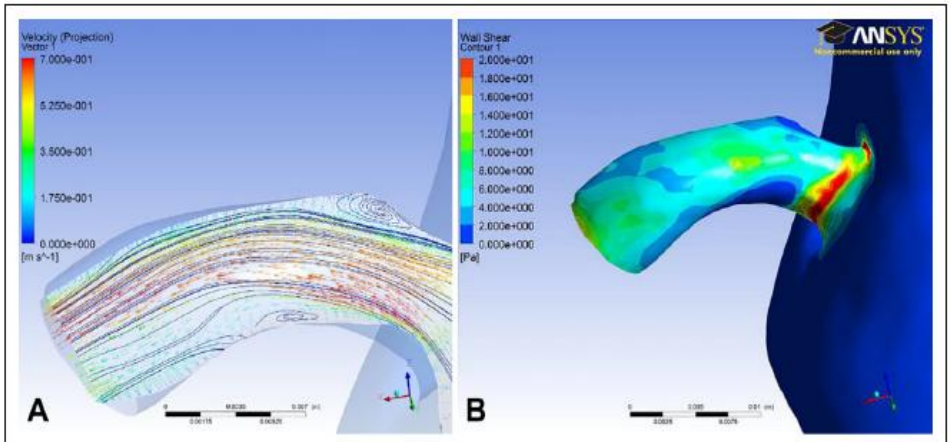
Moulakakis et al., VES; 2019, 53:572-82

FEVAR or chimneys?



Distribution of Supraceliac Aorta Flow (g/s)	Celiac Artery	Right Renal Artery	Left Renal Artery
Patient (A) treated with chimney grafts			
Before repair (%)	4.4 (10.0)	6.9 (15.7)	9.5 (21.6)
After repair (g/s) (%)	4.7 (10.7)	3.9 (8.9)	4.5 (10.2)
Patient (B) treated with fenestrated endograft			
Before repair (%)	6.0 (13.6)	8.8 (20.0)	9.8 (22.3)
After repair (g/s) (%)	8.4 (19.1)	7.5 (17.0)	8.3 (18.9)

[a]Time averaged mass flow rates were estimated (g/s).



Ελάττωση νεφρικής παροχής 43%-53% σε chimneys ≠ 15% σε αμφότερες τις νεφρικές του FEVAR

...and the quest continues!

Συμπεράσματα-ΙΙ

1. Οι γωνίες των νεφρικών κλάδων δεν επηρεάζουν τις δυνάμεις μετανάστευσης στα ενδομοσχεύματα FEVAR ή BRANCHED.
2. Οι μεταναστευτικές δυνάμεις επηρεάζονται από την πλάγια γωνία του ενδομοσχεύματος.
3. Η επάρκεια της νεφρικής παροχής δεν επηρεάζεται από τη διαμόρφωση των νεφρικών κλάδων (ορθόδρομα branches vs. ανάδρομα branches vs. Θυριδωτά branches). Εντούτοις ΠΟΣΟΤΙΚΑ η νεφρική παροχή: FEVAR>ορθόδρομα branches > ανάδρομα branches (αλλά μικρές διαφορές!)
4. Οι γωνίες των νεφρικών κλάδων (take-off angles) μπορούν να επηρεάσουν τις τιμές και την κατανομή του stress στα τμήματα εισαγωγής στις νεφρικές αρτηρίες.
5. Το μέγεθος της περιδίνησης (recirculation) στους νεφρικούς κλάδους εξαρτάται σημαντικά από τη γωνία του νεφρικού κλάδου

Συμπεράσματα-ΙΙ

6. Η ζώνη μετάβασης ανάμεσα στο τμήμα εισαγωγής (mating segment) του κλάδου και την αρτηρία υπόκειται στο υψηλότερο stress.

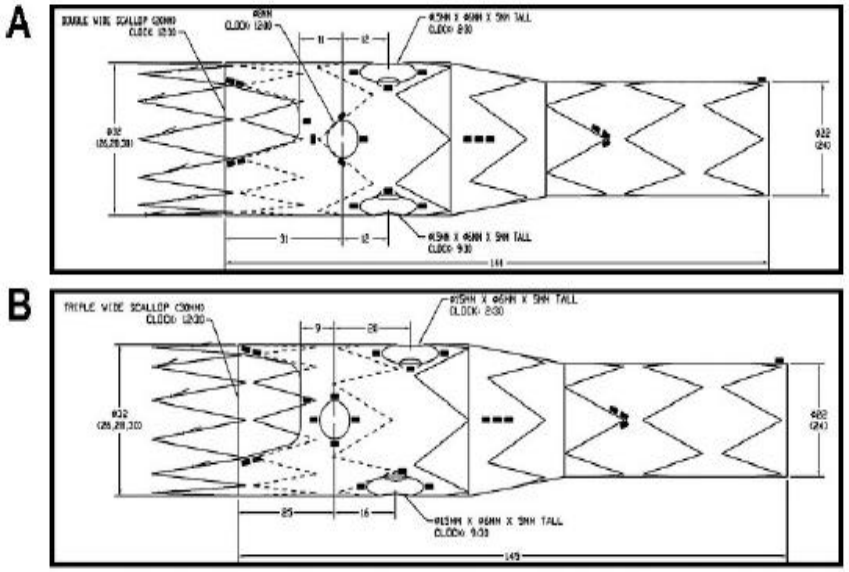
7. Η νεφρική παροχή φαίνεται να υπερέχει σε FEVAR απ'ότι ChEVAR

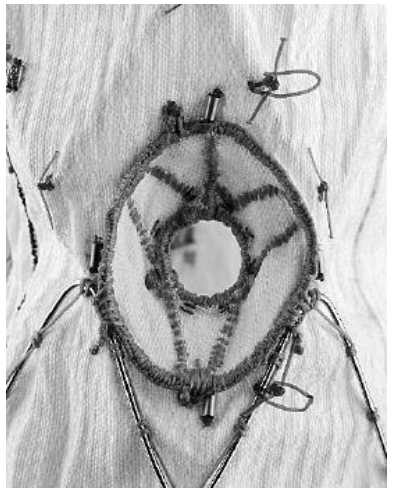
8. Τα συγκρίσιμα, πάντως, πρότυπα δυνάμεων και τάσεων μεταξύ των διαφόρων γωνιών των νεφρικών stent θα μπορούσαν να δικαιολογήσουν την επιτυχή αντιμετώπιση πολλών παρανεφρικών ανευρυσμάτων με μόλις 2 σχέδια off-the-shelf fenestrated μοσχευμάτων (Sobokinsky et al., JEVT 2012; 19: 165-72)

TABLE 1
Anatomical Criteria for an Off-the-Shelf Fenestrated Stent-Graft

	Stent-Graft Design 1	Stent-Graft Design 2
Proximal aortic sealing zone diameter, mm	22–31	22–31
Lengths		
Top of the graft to the aortic bifurcation, mm	≥164	≥165
Bottom of the CT to the center of the SMA, mm	>9	>7
Center of the LRA to the center of the SMA, mm	5–19	13–27
Center of the RRA to the center of the SMA, mm	5–19	9–23
Clock positions		
Center of the CT	11:30–13:30	10:30–13:30
Center of the LRA	02:00–03:00	02:00–03:00
Center of the RRA	09:00–10:00	09:00–10:00

CT: celiac trunk, LRA: left renal artery, RA: renal artery, RRA: right renal artery, SMA: superior mesenteric artery.





ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

ΜΗΧΑΝΙΚΕΣ ΙΔΙΟΤΗΤΕΣ ΤΩΝ STENT

- ✓ΕΡΓΑΣΤΗΡΙΑΚΗ ΠΡΟΣΕΓΓΙΣΗ (IN VITRO)
- ✓ΜΗΧΑΝΙΚΕΣ ΠΑΡΑΜΕΤΡΟΙ

Δομικές -Μηχανικές ιδιότητες των διαφόρων stents

J ENDOVASC THER
2013;20:523–535

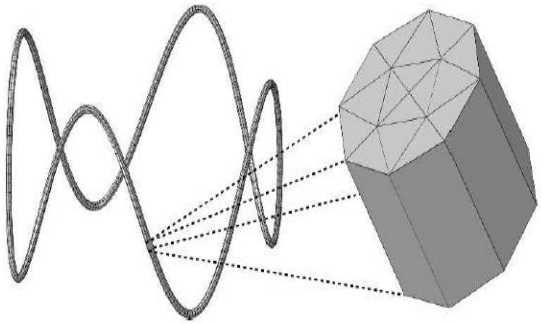


TABLE 3
Material Properties of 316L Stainless Steel, Nitinol, and Two Graft Fabrics

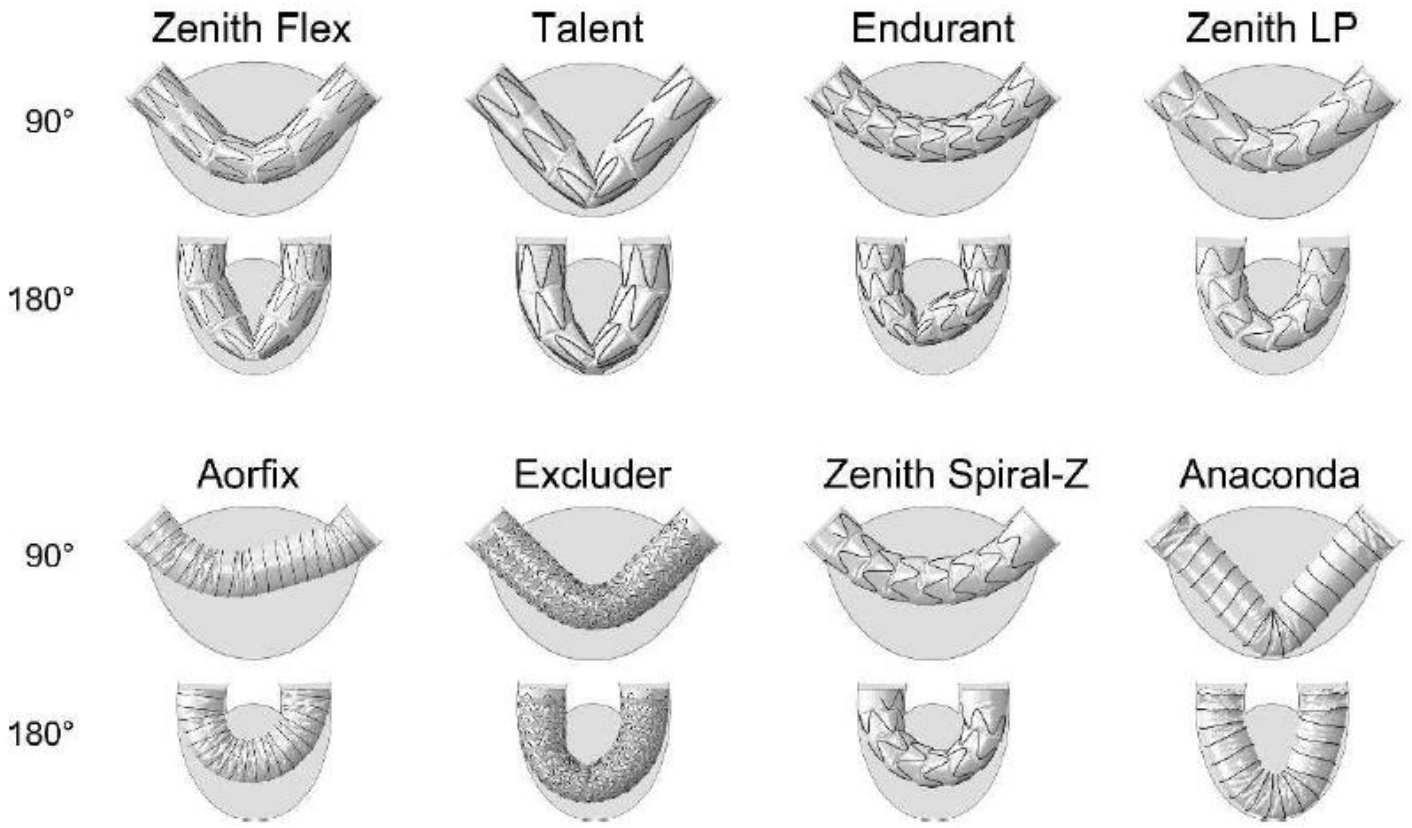
316L Stainless steel	
Young's modulus E, MPa	210000
Poisson's ratio ν	0.3
Yield stress σ_e, MPa	1550
Ultimate tensile strength σ_R, MPa	>2300
Nitinol[21]	
Austenite elasticity E_A, MPa	40000
Austenite Poisson's ratio ν_A	0.46
Martensite elasticity E_M, MPa	18554
Martensite Poisson's ratio ν_M	0.46
Transformation strain ε^L	0.04
Start of transformation loading σ_L^S, MPa	390
End of transformation loading σ_L^E, MPa	425
Ultimate tensile strength σ_R, MPa	827–1172
Expanded polytetrafluoroethylene[21,26]	
Young's modulus E, MPa	55.2
Poisson's ratio ν	0.46
Ultimate strain ε_R	0.2–0.477
Polyethylene terephthalate	
$E_{\theta=0^\circ}$ = longitudinal Young's modulus E_L, MPa	225±10%
$E_{\theta=90^\circ}$ = circumferential Young's modulus E_C, MPa	1000±10%
Poisson's ratio ν_{LC}	0.2
Shear modulus G, MPa	3.6
Longitudinal ultimate strain ε_R^L	0.23
Circumferential ultimate strain ε_R^C	0.18
Longitudinal bending stiffness D_L, $\times 10^{-4}$ N.mm	4.0
Circumferential bending stiffness D_C, $\times 10^{-4}$ N.mm	18

Εξέταση μηχανικής συμπεριφοράς των διαφόρων stent-grafts στην παραμόρφωση

J ENDOVASC THER
2013;20:523–535

◆EXPERIMENTAL INVESTIGATION◆

Finite Element Analysis of the Mechanical Performances of 8 Marketed Aortic Stent-Grafts



Conclusion: Stent design strongly influences mechanical performances of aortic stent-grafts. Spiral and circular stents provide greater flexibility, as well as lower stress values than Z-stents, and thus better durability.

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ
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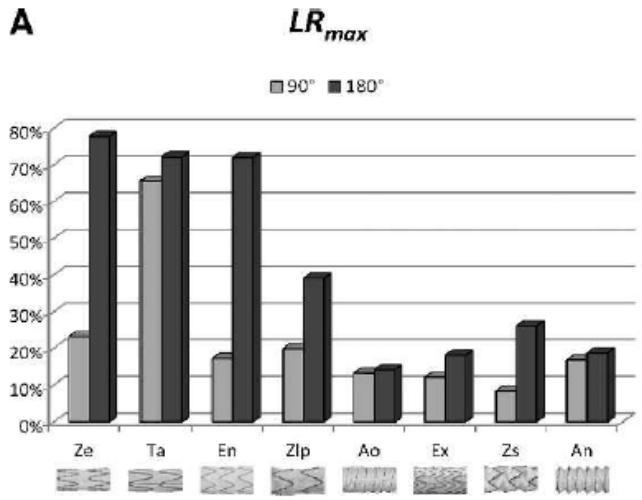
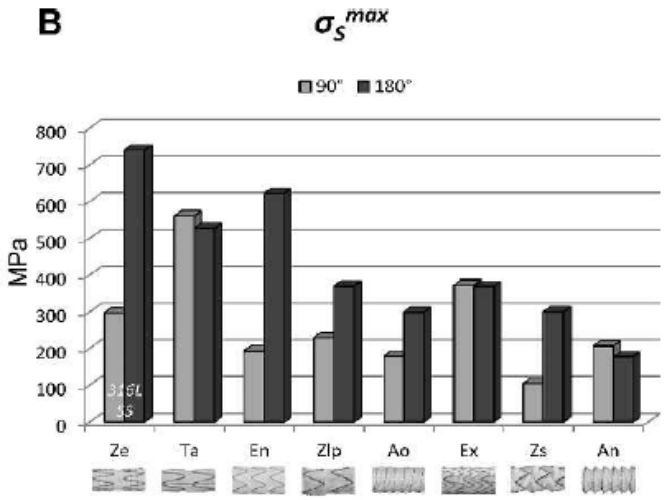
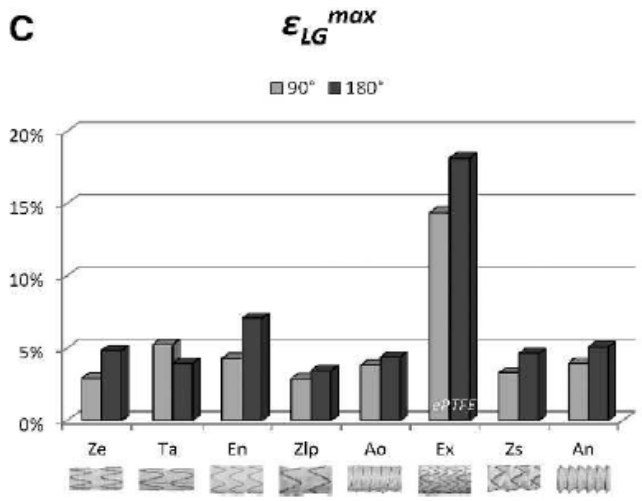
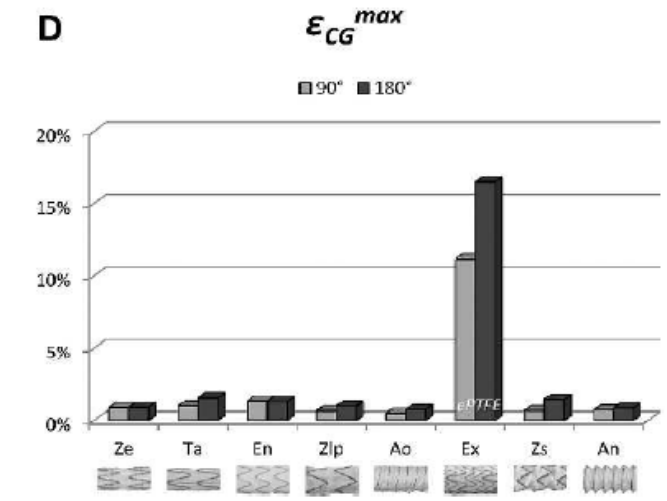
Ρυθμός μείωσης διαμέτρου (flexibility

stent: Μέγιστο Von Mises stres









Μέγιστη επιμήκης παραμόρφωση μοσχεύματος

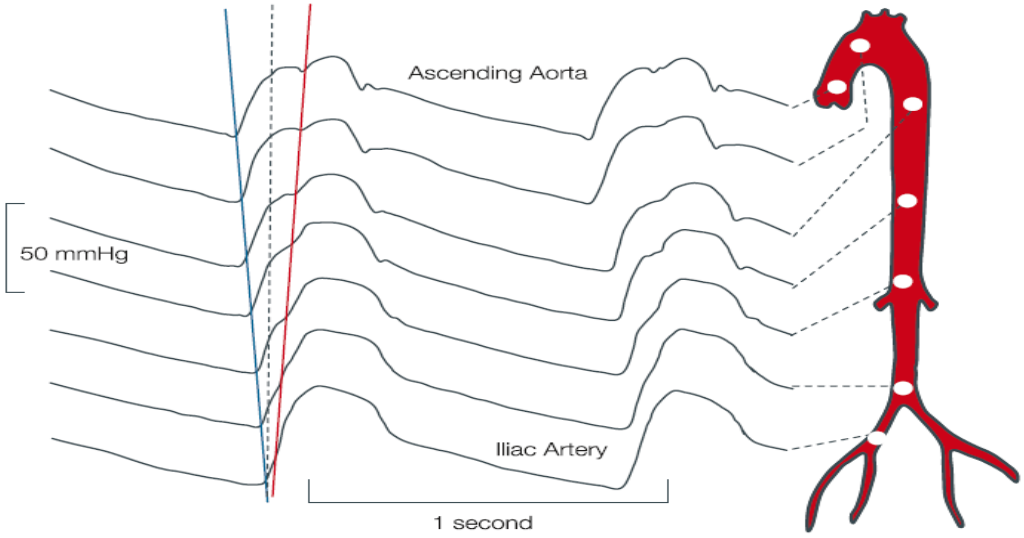
Μέγιστη περιμετρική παραμόρφωση μοσχεύματος

ΣΥΜΠΕΡΙΦΟΡΑ ΕΝΔΟΜΟΣΧΕΥΜΑΤΩΝ

ΚΕΝΤΡΙΚΗ ΚΥΚΛΟΦΟΡΙΑ

- ✓ΤΡΟΠΟΙ ΕΠΙΔΡΑΣΗΣ
- ✓ΜΗΧΑΝΙΚΕΣ ΠΑΡΑΜΕΤΡΟΙ

Επηρεάζει η EVAR την κεντρική αιμοδυναμική;



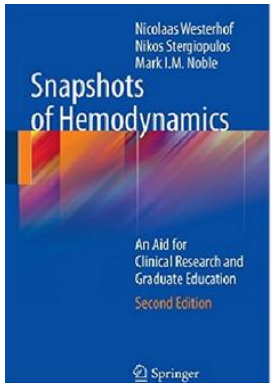
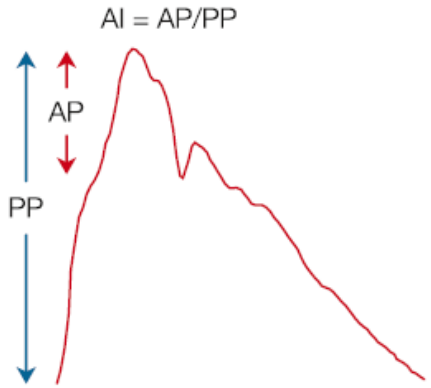
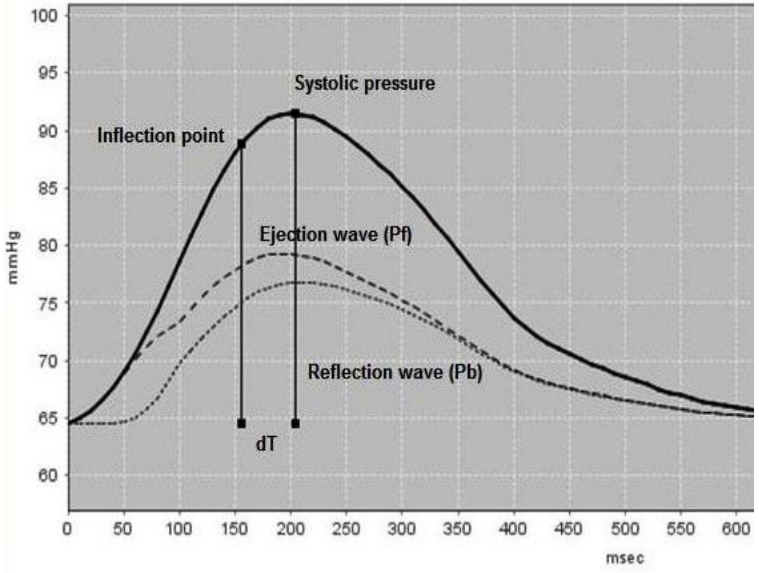


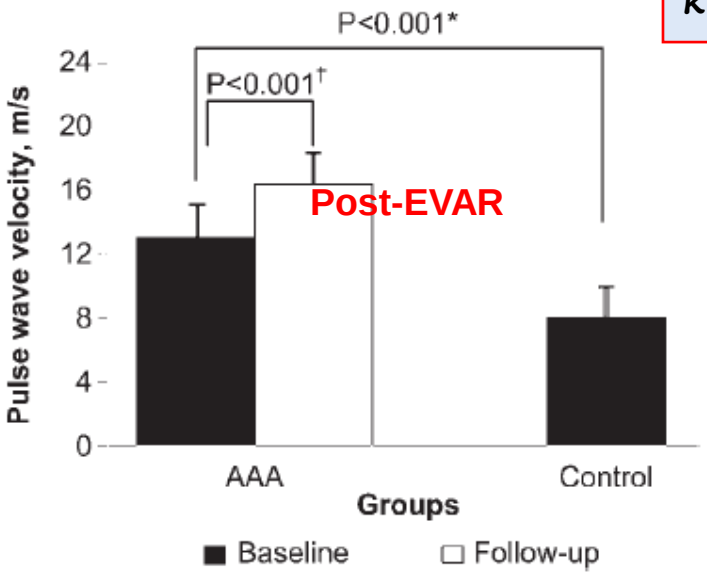
Fig. 21.2 The augmentation index (AI) is the augmented pressure (AP) divided by pulse pressure (PP). Calibration of blood pressure is not required





Changes in Aortic Pulse Wave Velocity of Patients Undergoing Endovascular Repair of Abdominal Aortic Aneurysms

J ENDOVASC THER
2012;19;661–666



Η ταχύτητα μετάδοσης του σφυγμικού κύματος (PWV) αυξάνει μετά από EVAR…

Differential Effects of Stent-Graft Fabrics on Arterial Stiffness in Patients Undergoing Endovascular Aneurysm Repair

J ENDOVASC THER
2014;21:850–858

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.

Διαφορετικά υλικά και δομικοί σχεδιασμοί των ενδομοσχευμάτων μπορεί να επάγουν διαφορετικές αιμοδυναμικές αποκρίσεις

Endovascular Aortic Repair Increases Vascular Stiffness and Alters Cardiac Structure and Function

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

… ήδη άμεσα μετεγχειρητικά (από την πρώτη εβδομάδα)!!!

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

Endovascular Aortic Repair Increases Vascular Stiffness and Alters Cardiac Structure and Function

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

… ενώ μακροχρόνια επηρεάζεται ΚΑΙ η καρδιακή λειτουργία (??)

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

Early Left Ventricular Global Longitudinal Strain Deterioration After Aortic Aneurysm Repair: Impact of Aortic Stiffness

Αποκλίσεις!!

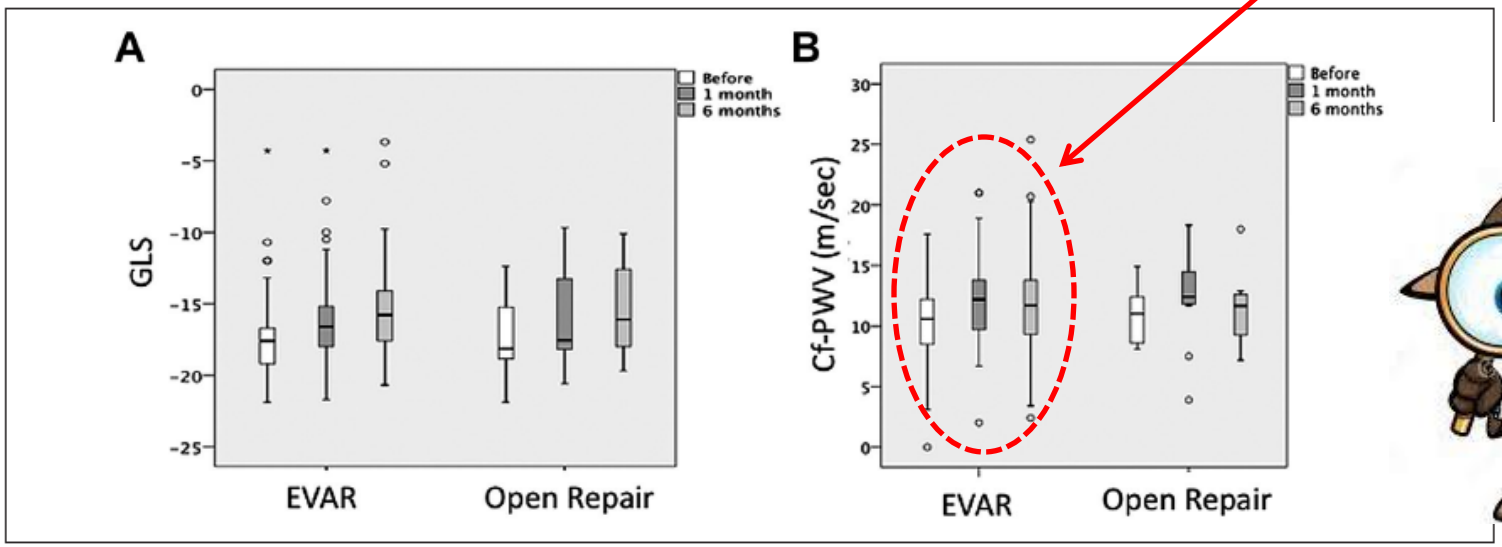
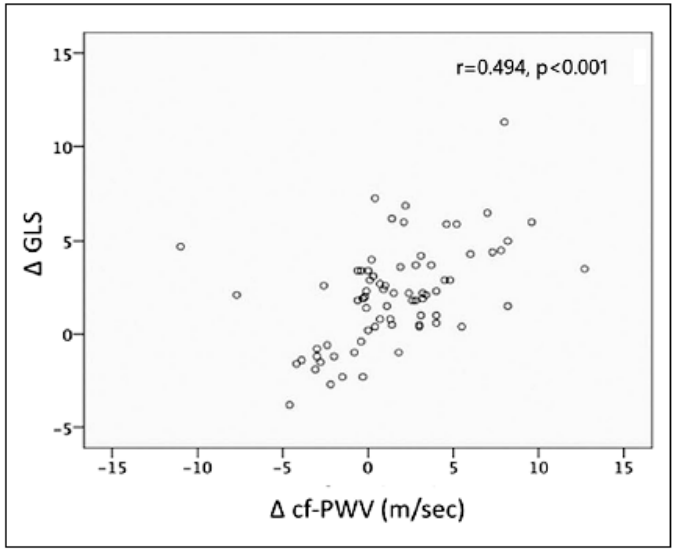


Figure 1. Levels of (A) global longitudinal strain (GLS) and (B) carotid-femoral pulse wave velocity (cf-PWV) preoperatively and at 1 and 6 months postoperatively. EVAR, endovascular aneurysm repair.

- ✓Παρά το μεγάλο δείγμα ασθενών (74) οριακή μόνο αύξηση του PWV από 10.2±3.1 σε 11.1±4.9 μετά από 1mo και σταθερό σε 6mo.
- ✓Αδύναμη συσχέτιση του PWV με GMS ή E/e'
- ✓Μετεγχειρητικές αλλαγές σε PWV ποικίλες (↓, ↑ ή σταθερό)



Marketou et al, JEVT; 2021: 352-9

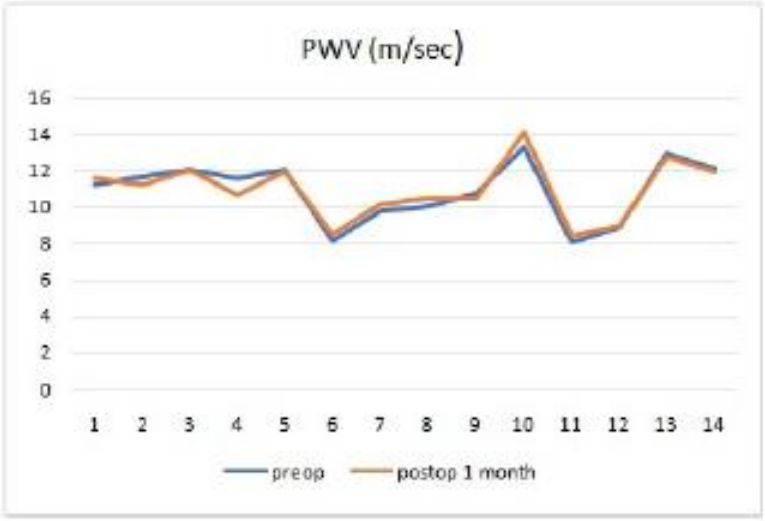
Ανέκδοτα αποτελέσματα σε 14 ασθενείς (Mobilograph)

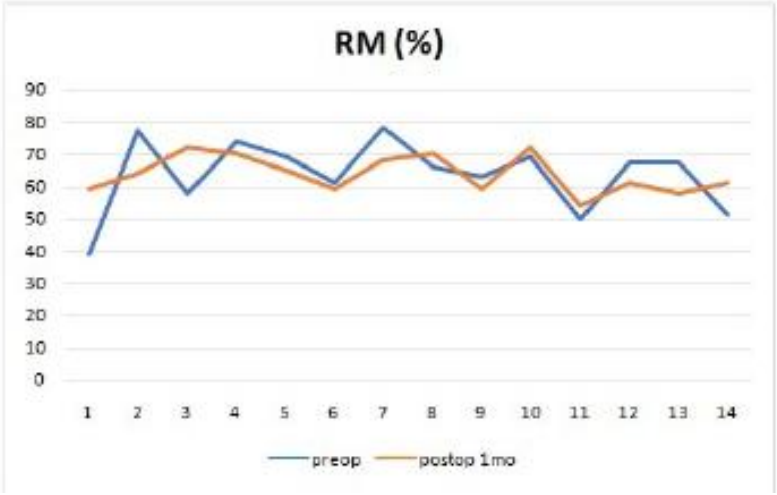
Table 1

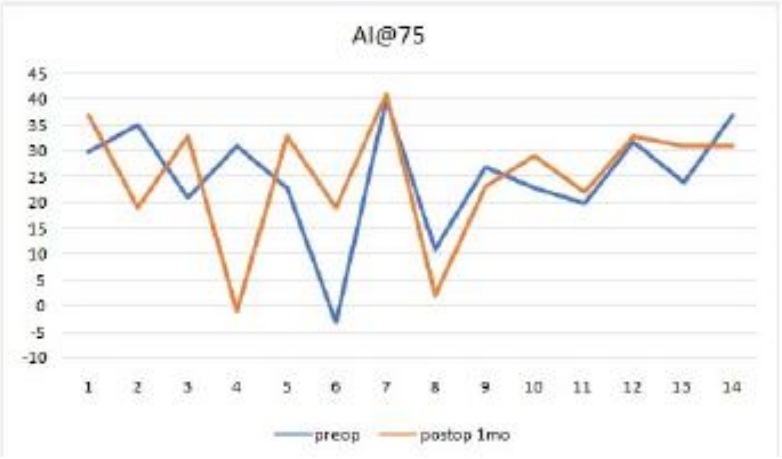
					Before EVAR				After EVAR			
	Age	Smoke	BMI	Type of graft	PWV (m/s)	AI@75	RM (%)	AP (mmHg)	PWV (m/s)	AI@75	RM (%)	AP (mmHg)
	70	Y	28.7	Endurant	11.2	30	39	14	11.6	37	59	21
	79	Y	23.4	Treovance	11.7	35	77	17	11.2	19	64	4
	74	Y	25.3	Endurant	12	21	58	12	12	33	72	21
	78	Y	24.2	Endurant	11.6	31	74	16	10.7	-1	70	3
	77	N	18.5	Treovance	12	23	69	22	11.9	33	65	19
	60	Y	26.7	Ovation	8.1	-3	61	1	8.5	19	59	5
	65	Y	33.2	Incraft	9.7	40	78	26	10.1	41	68	24
	70	N	25.6	Ovation	10	11	66	5	10.5	2	70	2
	69	Y	29.4	Treovance	10.7	27	63	10	10.5	23	59	4
	85	N	27.7	AFX	13.3	23	69	13	14.1	29	72	17
	52	N	25.8	Ovation	8	20	50	16	8.4	22	54	13
	61	Y	35.8	Excluder C3	8.8	32	67	20	8.9	33	61	16
	79	N	33.6	Treovance	12.9	24	67	17	12.7	31	58	9
	76	Y	19.5	Treovance	12.1	37	51	22	11.9	31	61	22
Average (mean±SD)	71±7	9/14	26.96±4.81		10.86±1.64	25.07±10.73	63.5±10.6	15.07±6.48	10.92±1.56	25.14±11.86	63.71±5.63	12.85±7.8

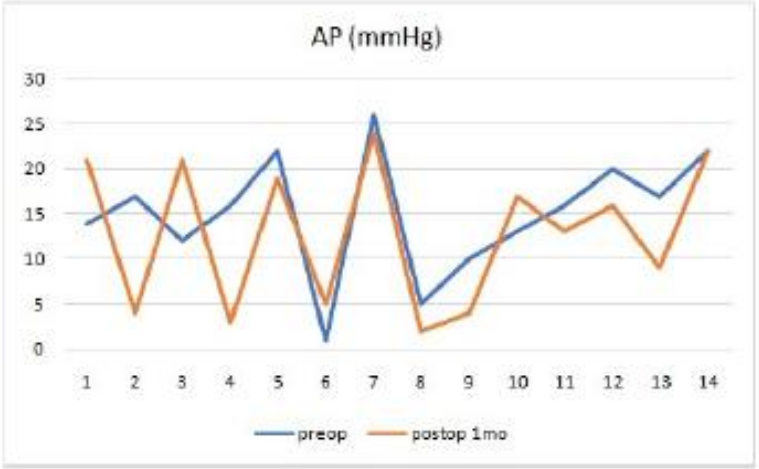
PWV; pulse wave velocity, AIx@75; augmentation index standardized to 75 beats-per-minute, RM; reflection magnitude, AP; augmentation pressure

For Peer Review









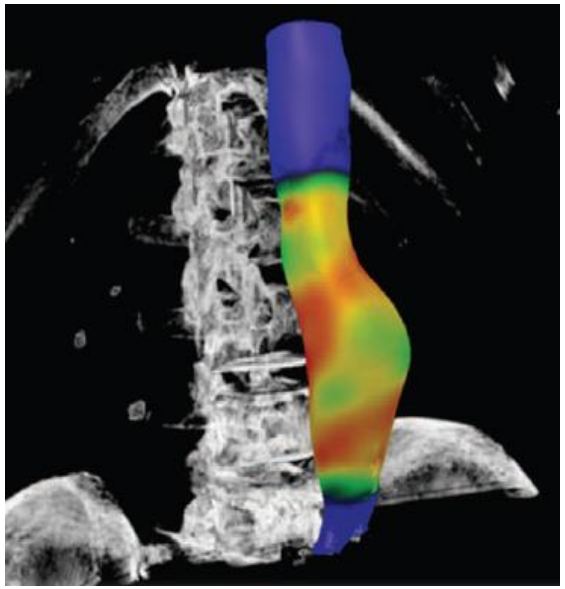
Οι μεταβολές αιμοδυναμικών παραγόντων όπως η πίεση ενίσχυσης (AP), συντελεστής ενίσχυσης (AI@75) και συντελεστής ανάκλασης (RM) δεν ακολουθούν πάντα τις μεταβολές PWV!!

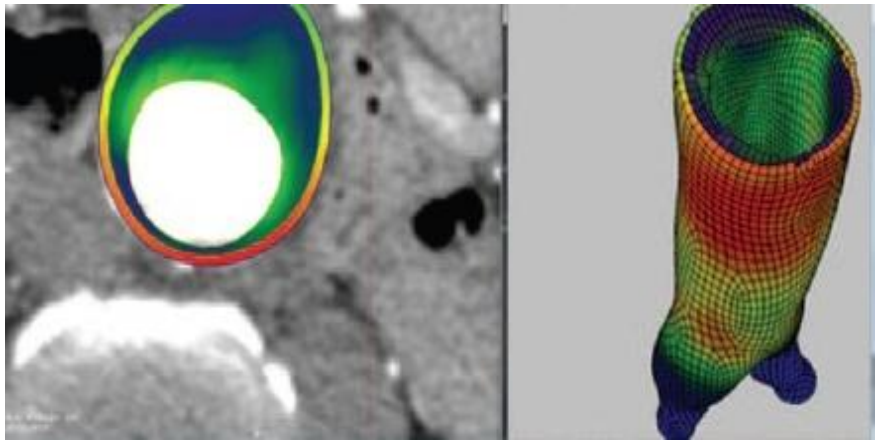
Εφαρμογές συμπερασμάτων υπολογιστικής προσομοίωσης στην κλινική πράξη

1. Ανάπτυξη αξιόπιστων software για ΚΑΘΗΜΕΡΙΝΗ ΚΛΙΝΙΚΗ ΠΡΑΞΗ user –friendly!
2. Εκτίμηση ΓΡΗΓΟΡΩΝ software για εκτίμηση μεταναστευτικών δυνάμεων και άλλων αιμοδυναμικών παραμέτρων ανάλογα με μόσχευμα και εξατομικευμένη γεωμετρία
3. Εφαρμογή συμπερασμάτων σε ΚΑΘΗΜΕΡΙΝΑ ΚΛΙΝΙΚΑ ΔΙΛΛΗΜΑΤΑ ΕΠΙΛΟΓΗΣ ΕΝΔΟΜΟΣΧΕΥΜΑΤΟΣ

Εκτίμηση κινδύνου ρήξης σε μικρά ΑΚΑ – Παράδειγμα

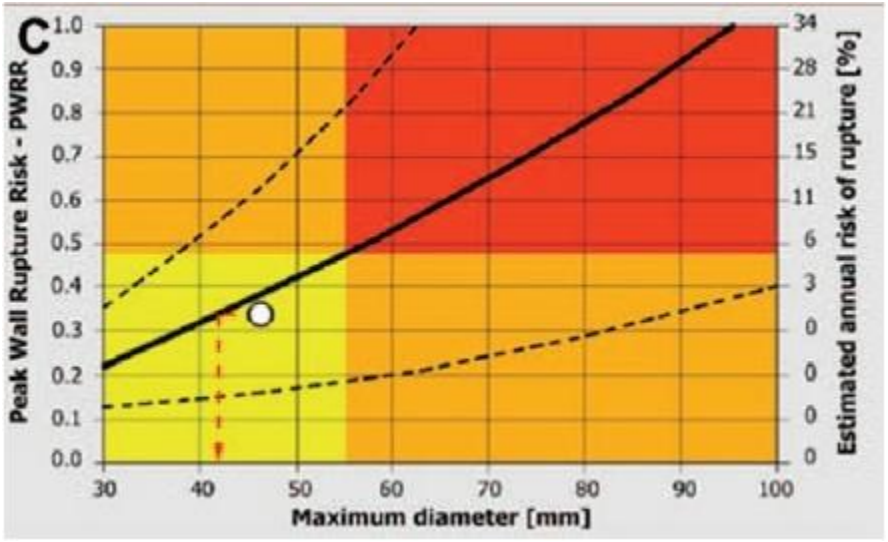
The Holy Grail of Vascular Surgery:
Estimation of AAA rupture risk

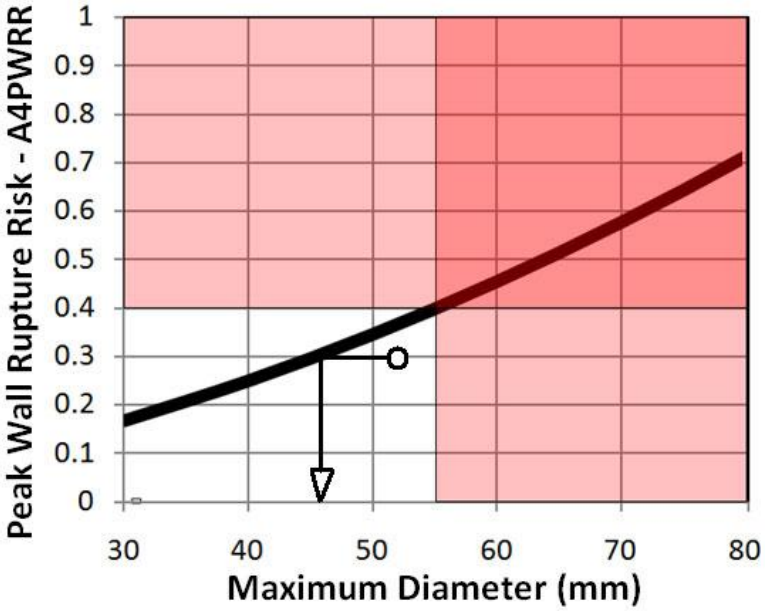




Georgakarakos et al, EJVES; 2014: 288-95

Εκτίμηση κινδύνου ρήξης σε μικρά ΑΚΑ– Παράδειγμα Ι





Estimation of rupture risk in small AAA: which at risk?

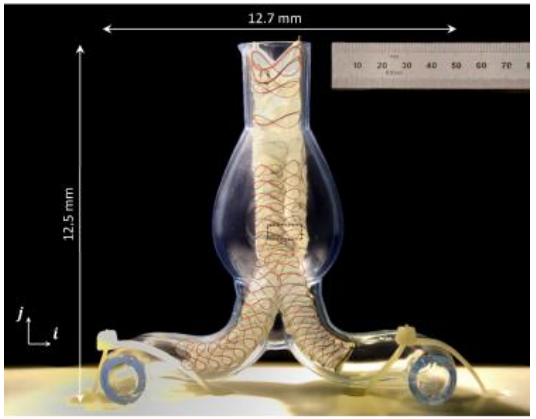
Down-sizing of an AAA 5.5 to 4.5cm !

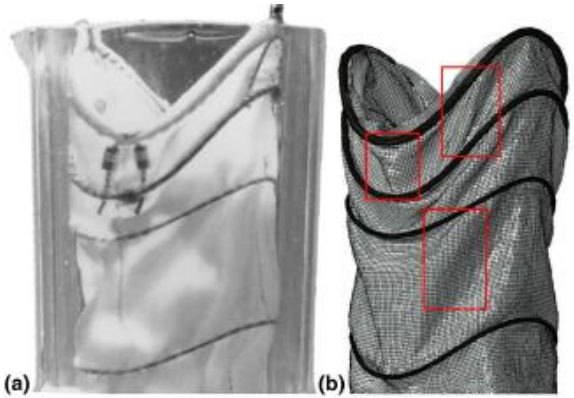
Georgakarakos et al, JEVT; 2014: 565-7

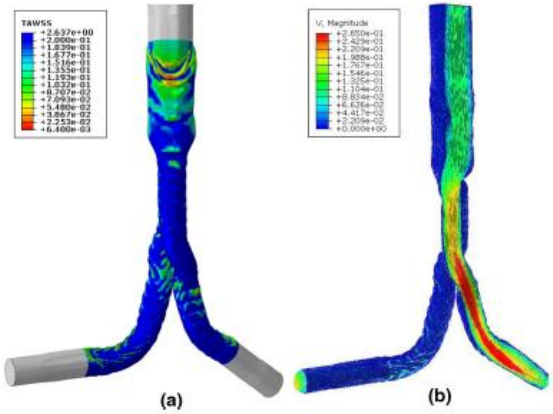
Efficiently Simulating an Endograft Deployment: A Methodology for Detailed CFD Analyses

FAIDON KYRIAKOU,[1] CRAIG MACLEAN,[2] WILLIAM DEMPSTER,[1] and DAVID NASH[1]

Abstract—Numerical models of endografts for the simulation of endovascular aneurysm repair are increasingly important in the improvement of device designs and patient outcomes. Nevertheless, current finite element analysis (FEA) models of complete endograft devices come at a high computational cost, requiring days of runtime, therefore restricting their applicability. In the current study, an efficient FEA model of the Anaconda™ endograft (Terumo Aortic, UK) was developed, able to yield results in just over 4 h, an order of magnitude less than similar models found in the literature. The model was used to replicate a physical device that was deployed in a 3D printed aorta and comparison of the two shapes illustrated a less than 5 mm placement error of the model in the regions of interest, consistent with other more computationally intensive models in the literature. Furthermore, the final goal of the study was to utilize the deployed fabric model in a hemodynamic analysis that would incorporate realistic fabric folds, a feature that is almost always omitted in similar simulations. By successfully exporting the deployed graft geometry into a flow analysis, it was illustrated that the inclusion of fabric wrinkles enabled clinically significant flow patterns such as flow stagnation and recirculation to be detected, paving the way for this modelling methodology to be used in future for stent design optimisation.







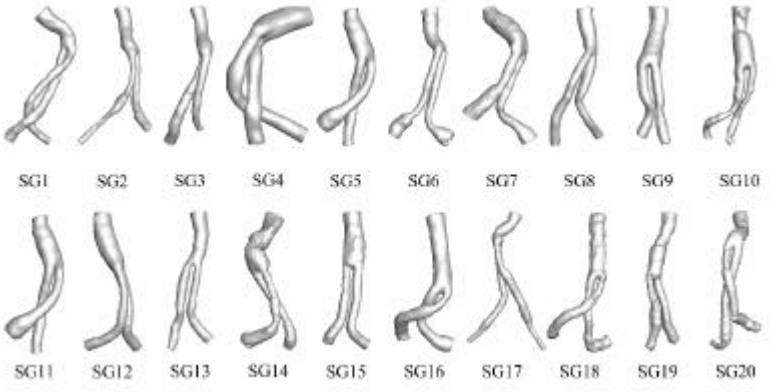
Ann Biomed Engin 2020; 48: 2449-65

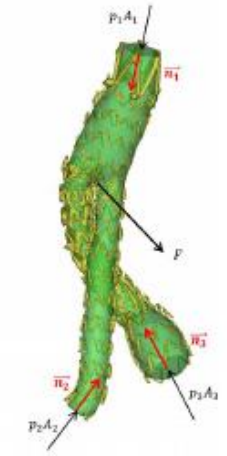
Fast and Accurate Computation of the Displacement Force of Stent Grafts after Endovascular Aneurysm Repair

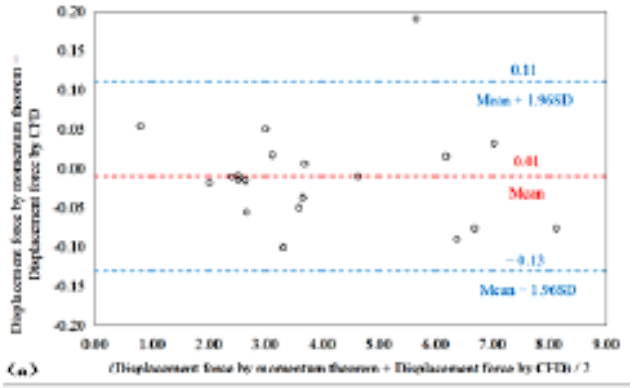
Ming Qing [1,2], Zhan Liu [1] and Tinghui Zheng [1,3,*]

Bioengineering 2022; 9: 447

Abstract: *Purpose:* Currently, the displacement force of stent grafts is generally obtained using computational fluid dynamics (CFD), which requires professional CFD knowledge to perform the correct simulation. This study proposes a fast, simple, and clinician-friendly approach to calculating the patient-specific displacement force after endovascular aneurysm repair (EVAR). *Methods:* Twenty patient-specific post-EVAR computed tomography angiography images were used to reconstruct the patient-specific three-dimensional models, then the displacement forces were calculated using CFD and the proposed approaches, respectively, and their numerical differences were compared and analyzed. *Results:* Based on the derivation and simplification of the momentum theorem, the patient-specific displacement forces were obtained using the information of the patient-specific pressure, cross-sectional area, and angulation of the two stent graft ends, and the average relative error was no greater than 1.37% when compared to the displacement forces calculated by CFD. In addition, the linear regression analysis also showed good agreement between the displacement force values calculated by the new approach and CFD (R = 0.999). *Conclusions:* The proposed approach can quickly and accurately calculate the patient-specific displacement force on a stent graft and can therefore help clinicians quickly evaluate the post-EVAR displacement force.







Fast Approximate Quantification of Endovascular Stent Graft Displacement Forces in the Bovine Aortic Arch Variant

JOURNAL OF ENDOVASCULAR THERAPY
A SAGE Publication
An official publication of the ISEVS

Journal of Endovascular Therapy
1–13
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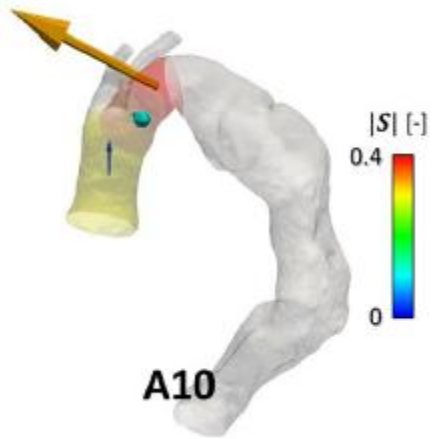
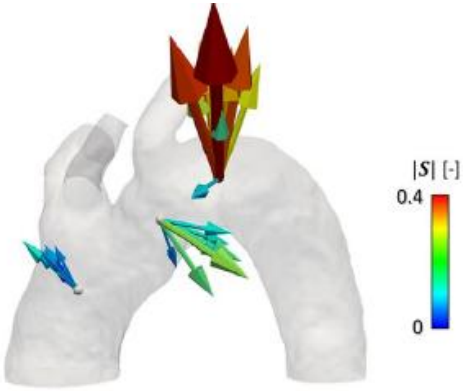
DOI: 10.1177/15266028221095403

Francesco Sturla, PhD[1,2], Alessandro Caimi, PhD[2], Rodrigo M. Romarowski, PhD[1], Giovanni Nano, MD[3,4], Mattia Glauber, MD[5], Alberto Redaelli, PhD[2], Emiliano Votta, PhD and Massimiliano M. Marrocco-Trischitta, MD, PhD[3,6]

Abstract

Purpose: Displacement forces (***DF***s) identify hostile landing zones for stent graft deployment in thoracic endovascular aortic repair (TEVAR). However, their use in TEVAR planning is hampered by the need for time-expensive computational fluid dynamics (CFD). We propose a novel fast-approximate computation of ***DF***s merely exploiting aortic arch anatomy, as derived from the computed tomography (CT) and a measure of central aortic pressure. **Materials and Methods:** We tested the fast-approximate approach against CFD gold-standard in 34 subjects with the "bovine" aortic arch variant. For each dataset, a 3-dimensional (3D) model of the aortic arch lumen was reconstructed from computed tomography angiography and CFD then employed to compute ***DF***s within the aortic proximal landing zones. To quantify fast-approximate ***DF***s, the wall shear stress contribution to the ***DF*** was neglected and blood pressure space-distribution was averaged on the entire aortic wall to reliably approximate the patient-specific central blood pressure. Also, ***DF*** values were normalized on the corresponding proximal landing zone area to obtain the equivalent surface traction (***EST***). **Results:** Fast-approximate approach consistently reflected (r^2=0.99, $p<0.0001$) the ***DF*** pattern obtained by CFD, with a −1.1% and 0.7° bias in ***DF***s magnitude and orientation, respectively. The normalized ***EST*** progressively increased ($p<0.0001$) from zone 0 to zone 3 regardless of the type of arch, with proximal landing zone 3 showing significantly greater forces than zone 2 ($p<0.0001$). Upon ***DF*** normalization to the corresponding aortic surface, fast-approximate ***EST*** was decoupled in blood pressure and a dimensionless shape vector (***S***) reflecting aortic arch morphology. ***S*** showed a zone-specific pattern of orientation and proved a valid biomechanical blueprint of ***DF*** impact on the thoracic aortic wall. **Conclusion:** Requiring only a few seconds and quantifying clinically relevant biomechanical parameters of proximal landing zones for arch TEVAR, our method suits the real preoperative decision-making process. It paves the way toward analyzing large population of patients and hence to define threshold values for a future patient-specific preoperative TEVAR planning.



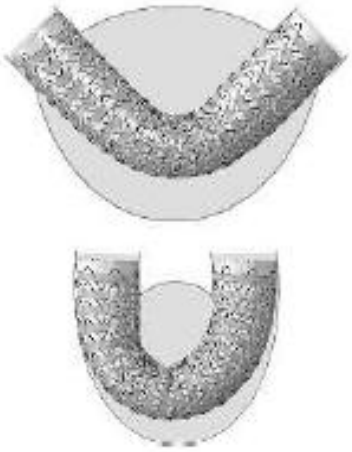


Αιμοδυναμικές παρατηρήσεις στη χρήση υβριδικών συνδυασμών ενδομοσχευμάτων

Zenith main body

+

Excluder



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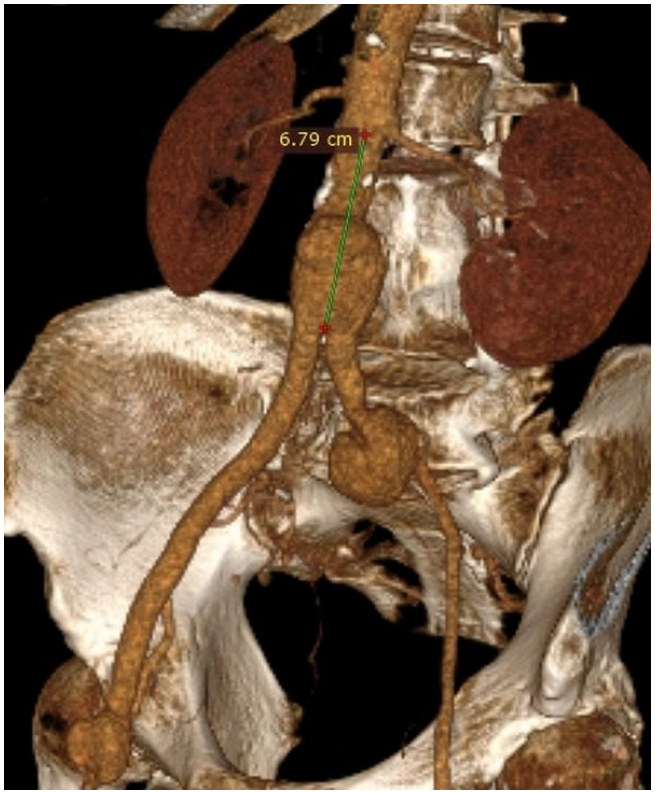
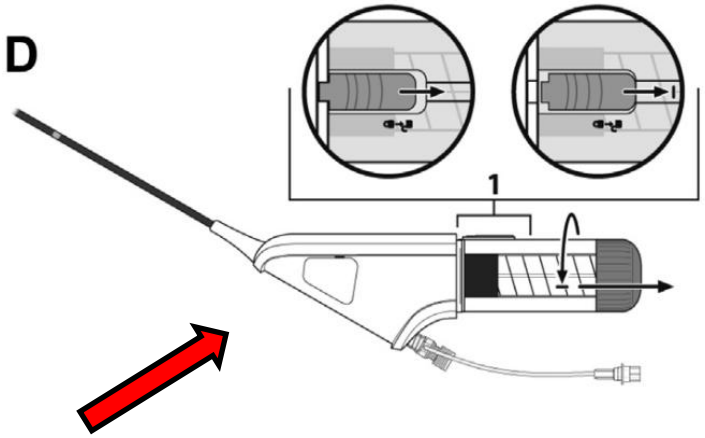
Χρήση εύκαμπτων σκελών σε μεγάλες ελικώσεις (Gore, Excluder) σε υβριδικούς σχεδιασμούς

Bos et al., Vascular;. 2010; 18: 136-40
Georgiadis et al., In t J Artif Organs 2013; 36: 28-38

ΥΠΑΡΧΟΥΝ ΠΡΟΒΛΗΜΑΤΑ ΠΟΥ ΔΕΝ ΜΠΟΡΟΥΝ ΝΑ ΠΡΟΣΕΓΓΙΣΤΟΥΝ / ΕΚΤΙΜΗΘΟΥΝ ΠΑΡΑ ΜΟΝΟ ΜΕ ΥΠΟΛΟΓΙΣΤΙΚΕΣ ΜΕΘΟΔΟΥΣ ΠΡΟΣΟΜΕΙΩΣΗΣ:

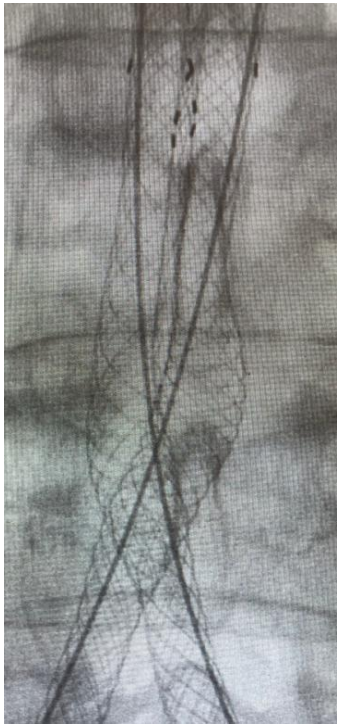




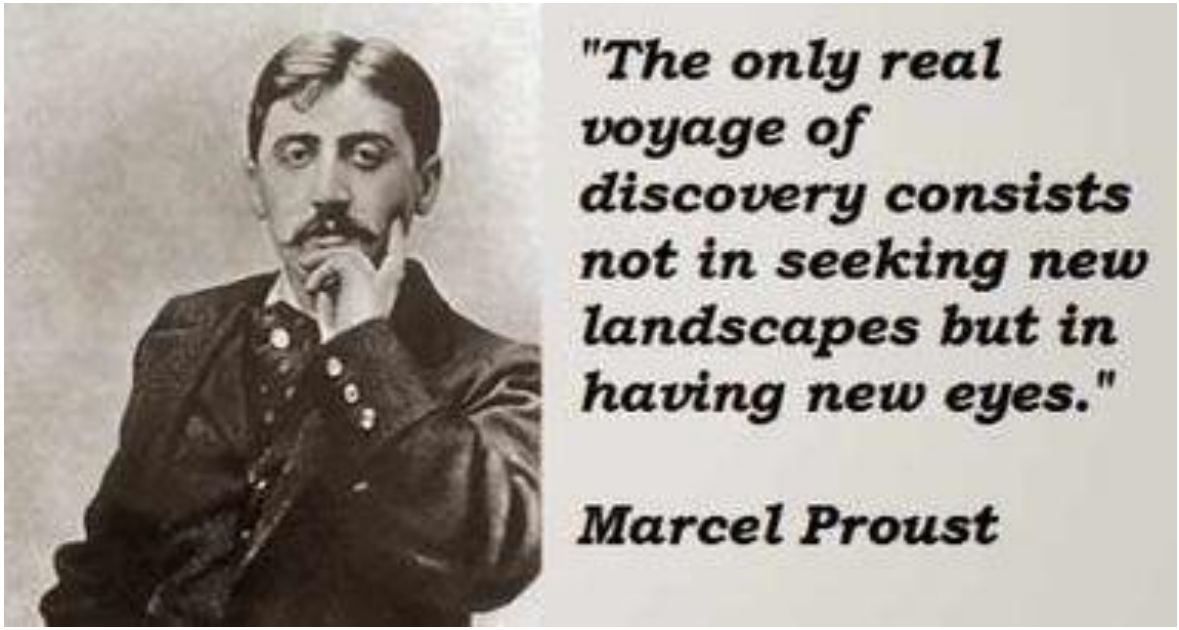
Gore (repositionable)

ΕΠΙΛΟΓΕΣ???

Altura (no main-body)



Treo custom-short body


"The only real voyage of discovery consists not in seeking new landscapes but in having new eyes."
Marcel Proust