UNIVERZITET U NOVOM SADU
PRIRODNO-MATEMATIČKI
FAKULTET
DEPARTMAN ZA FIZIKU

Simulacije protoka krvi kroz aneurizmu abdominalne aorte (AAA): nove mogućnosti

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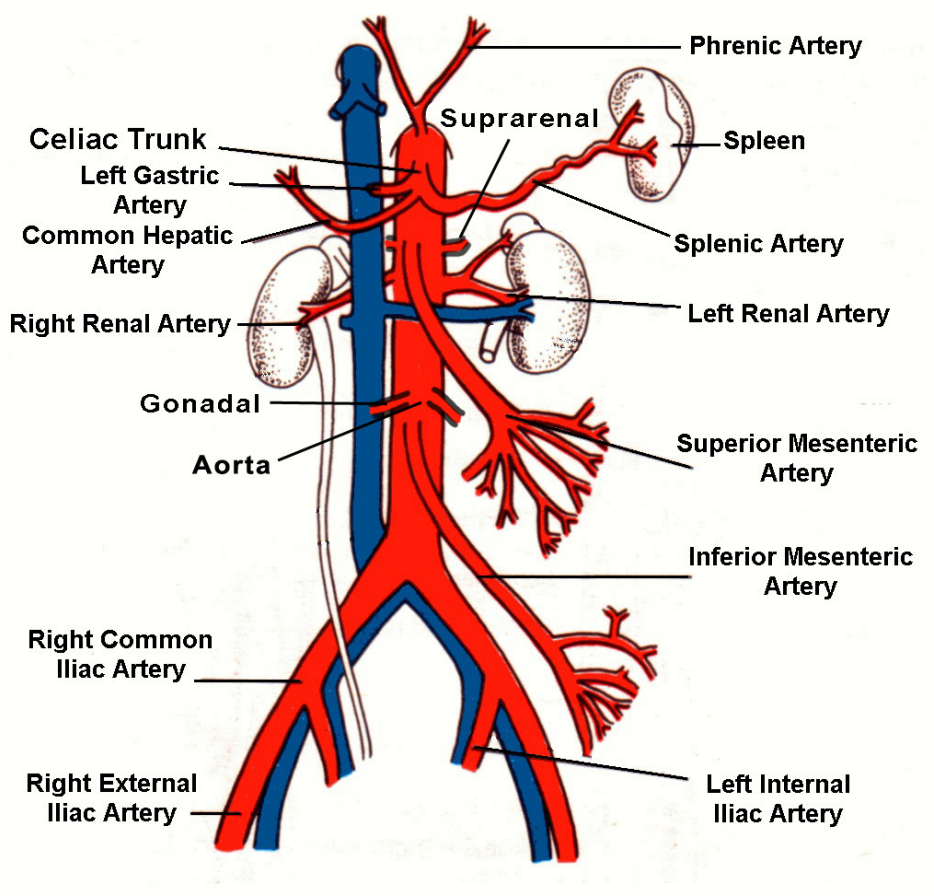
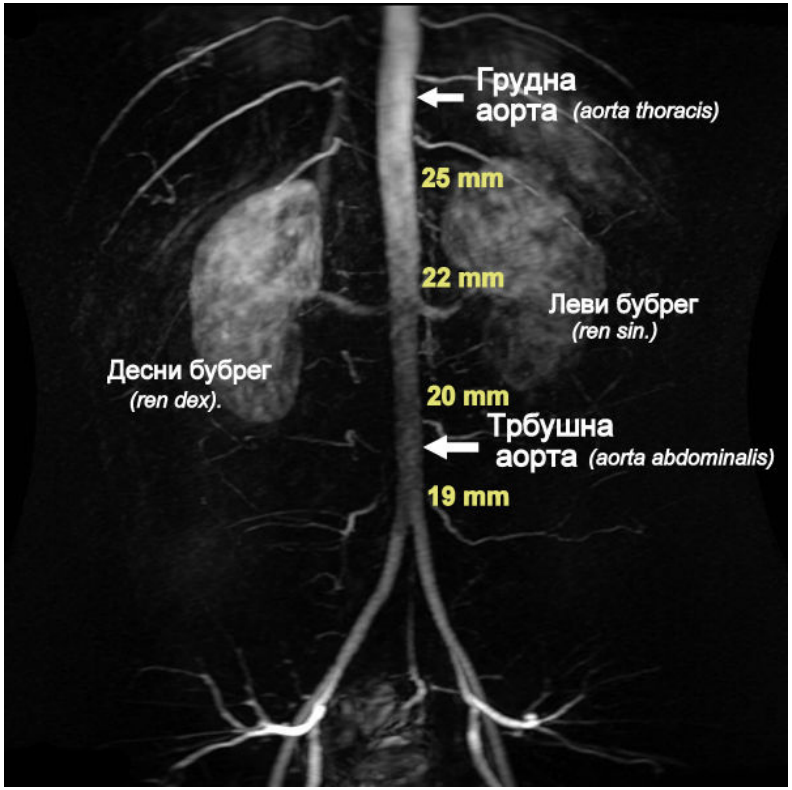
Sadržaj

- Medicinska osnova
  - Anatomija i histologija AA
  - Uzroci nastanka AAA
- Teorijska osnova
  - La Place-ova jednačina
  - RSM
  - Von Misses napon
- Metode i rezultati
  - Rekonstrukcija krvnog suda
  - Simulacije (brzina, pritisak, napon)

Medicinska osnova

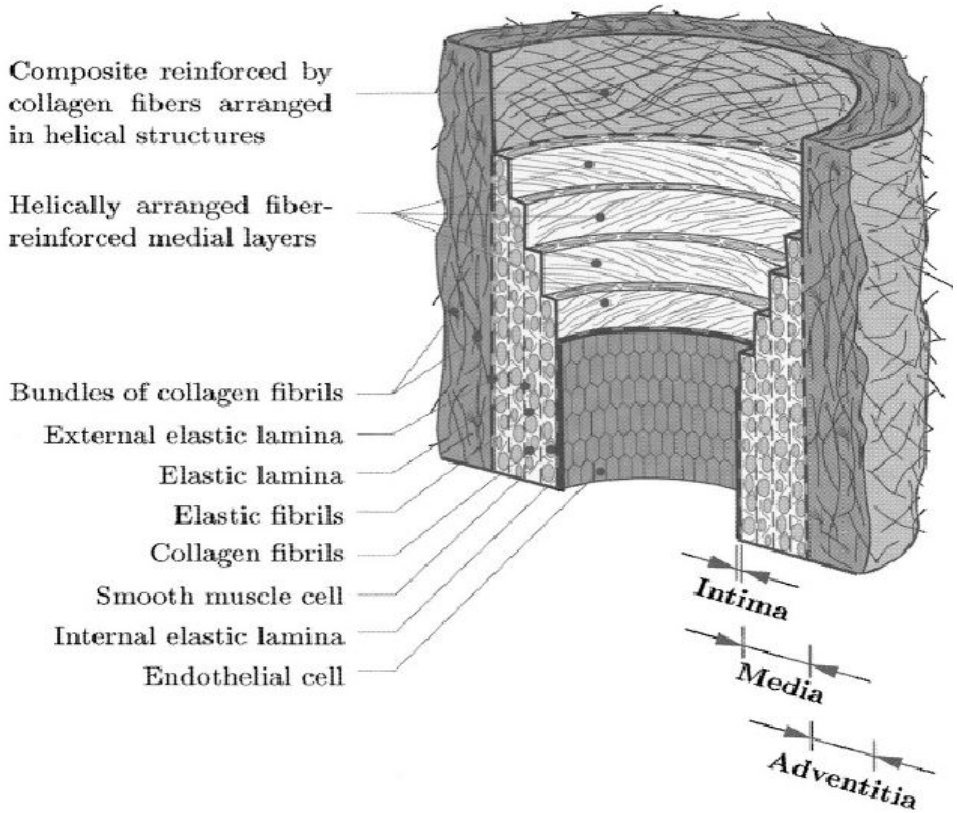
- Abdominalna aorta (AA)





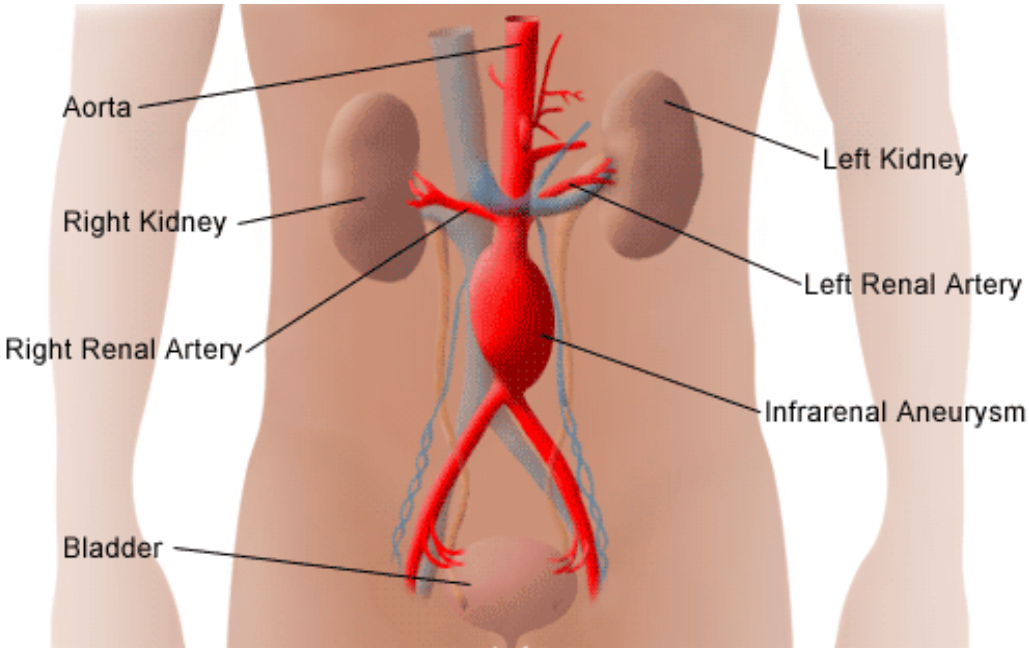
Medicinska osnova

- Arterijski zidovi sastavljeni su od tri sloja:
  - Intima
  - Media (glatke mišićne ćelije, **v**lakna elastina i kolagena)
  - Adventitia (vlakna kolagena)



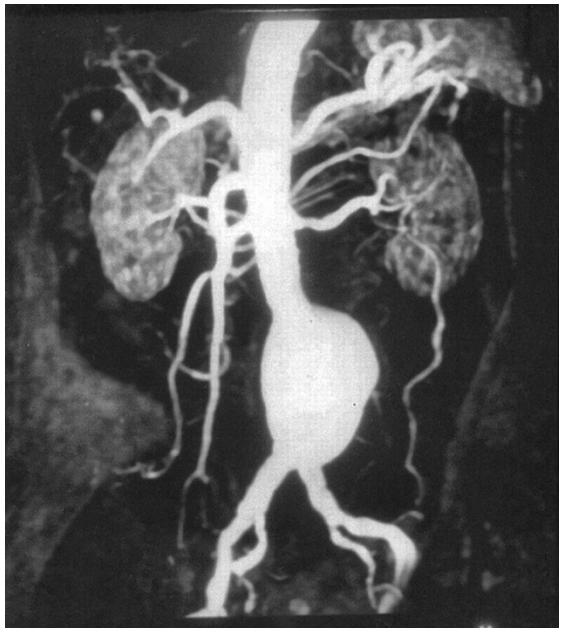
Medicinska osnova

- Aneurizma abdominalne aorte (AAA): mehurasta, ireverzibilna, fokalna dilatacija!
- Definicija:
  - Aorta sa infrarenalnim dijametrom većim od 3cm.
  - Infrarenalni dijametar 1,5 puta veći od normalnog.

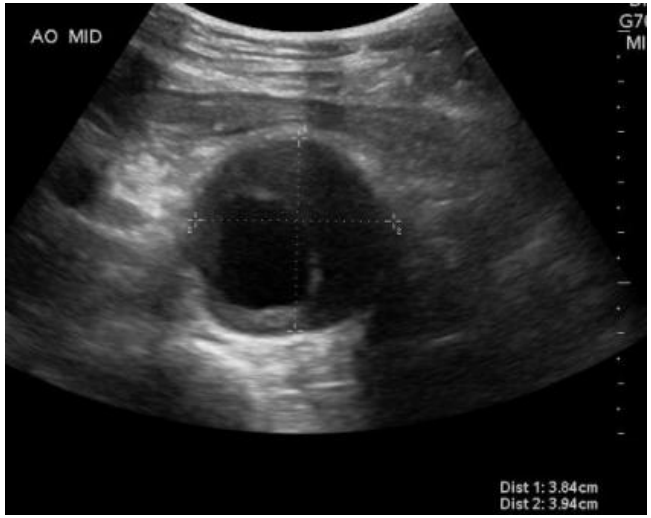


Medicinska osnova

- Pr**o**blem – Asimptomatičan



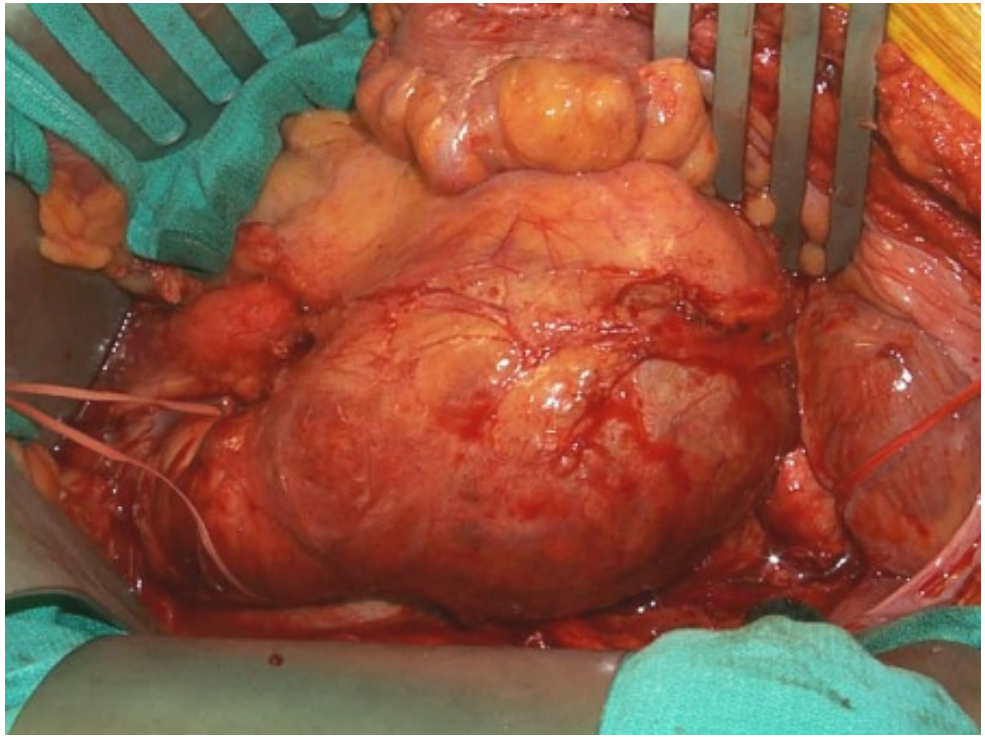
Angiografija

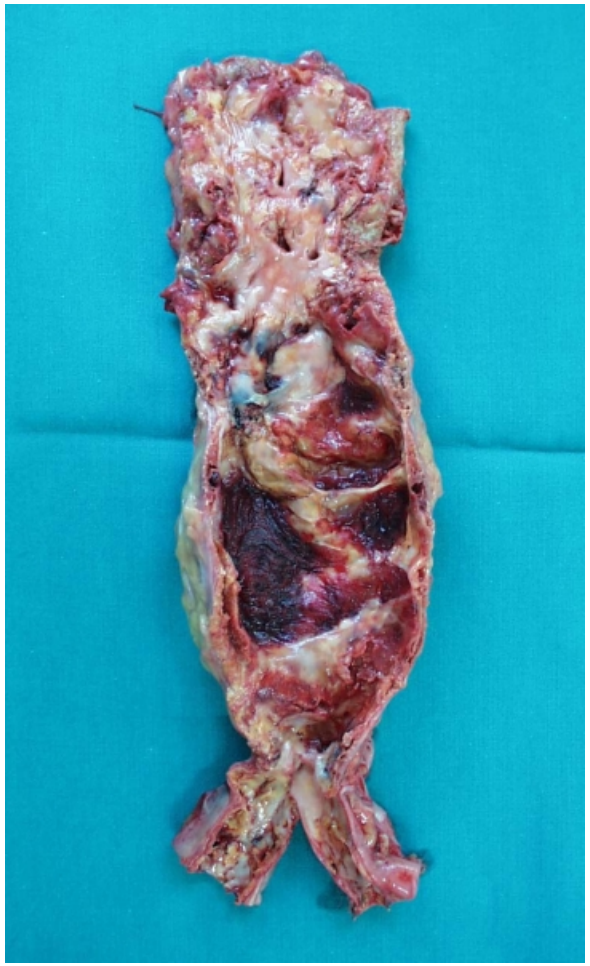


UZ

CT

Medicinska osnova





Medicinska osnova

- Faktori rizika:
  - Hronično pušenje duvana-najbitniji spoljašnji faktor.
  - Hronični alkoholizam
  - Hipertenzija
  - Genetski uticaj
  - Pol

Medicinska osnova

- Gubitak elastičnih vlakana je prvi korak u formiranju aneurizme.
- Degradacija kolagena je glavni uzrok rupture.
- Redukcija broja glatkih mišićnih ćelija!
- Često se javlja i intraluminalni tromb!

Medicinska osnova-Prognoza rupture

- Ruptura (biomeh.): mehanički napon zida premaši otpornost na istezanje zida.
- Trenutni standard: maksimalni dijametar (>5.5 cm)(kriterijum se ne zasniva na mehaničkim osobinama zida).
- Loša statistika

AAA Diameter (cm)	Stopa rasta (cm/god)	Rizik od rupture (%)
3,0-3,9	0,39	0
4,0-4,9	0,36	0,5-5
5,0-5,9	0,43	3-15
6,0-6,9	0,64	10-20
>7	-	20-50

Teorijska osnova

- Laplace jednačina: $\sigma = \frac{pr}{ct}$
- Reynolds Stress Model (RSM): najkompleksniji model za simulaciju turbulentnog protoka fluida

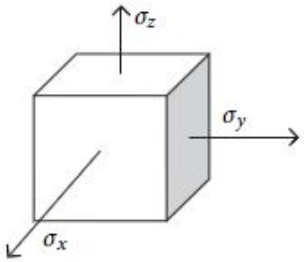
$$\underbrace{\frac{\partial}{\partial t}(\rho\,\overline{u_i'u_j'})}_{\text{Local Time Derivative}} + \underbrace{\frac{\partial}{\partial x_k}(\rho u_k \overline{u_i'u_j'})}_{C_{ij}\,\equiv\,\text{Convection}} = \underbrace{-\frac{\partial}{\partial x_k}\left[\rho\,\overline{u_i'u_j'u_k'} + \overline{p\left(\delta_{kj}u_i' + \delta_{ik}u_j'\right)}\right]}_{D_{T,ij}\,\equiv\,\text{Turbulent Diffusion}}$$

$$+ \underbrace{\frac{\partial}{\partial x_k}\left[\mu\frac{\partial}{\partial x_k}(\overline{u_i'u_j'})\right]}_{D_{L,ij}\,\equiv\,\text{Molecular Diffusion}} \underbrace{-\rho\left(\overline{u_i'u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j'u_k'}\frac{\partial u_i}{\partial x_k}\right)}_{P_{ij}\,\equiv\,\text{Stress Production}} \underbrace{-\rho\beta(g_i\overline{u_j'\theta} + g_j\overline{u_i'\theta})}_{G_{ij}\,\equiv\,\text{Buoyancy Production}}$$

$$+ \underbrace{\overline{p\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)}}_{\phi_{ij}\,\equiv\,\text{Pressure Strain}} - \underbrace{2\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}}}_{\epsilon_{ij}\,\equiv\,\text{Dissipation}}$$

$$\underbrace{-2\rho\Omega_k\left(\overline{u_j'u_m'}\epsilon_{ikm} + \overline{u_i'u_m'}\epsilon_{jkm}\right)}_{F_{ij}\,\equiv\,\text{Production by System Rotation}} + \underbrace{S_{\text{user}}}_{\text{User-Defined Source Term}}$$

- Von Misses napon: $\sigma_{VM} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_x - \sigma_z)^2}{2}}$



Metode

- Medicinski podaci pacijenata:

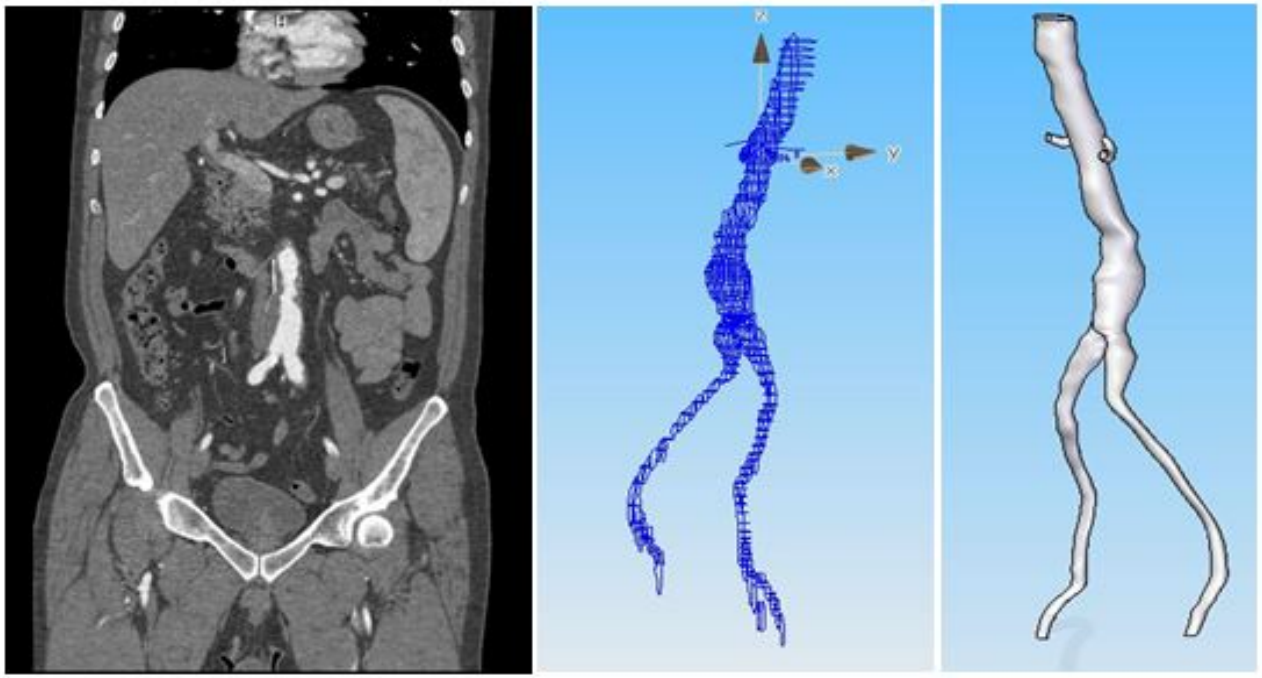
	Starost [Godina]	Maksimalni dijametar [cm]
Pacijent 1	65	4,2
Pacijent 2	76	6,0
Pacijent 3	78	5,6
Pacijent 4	69	5,4

- Svi pacijenti muškog roda!!!
- Za dobijanje 2D slika korišćen je CT
- Za merenje dijametra i brzine protoka US

Metode-Rekonstrukcija 3D geometrije

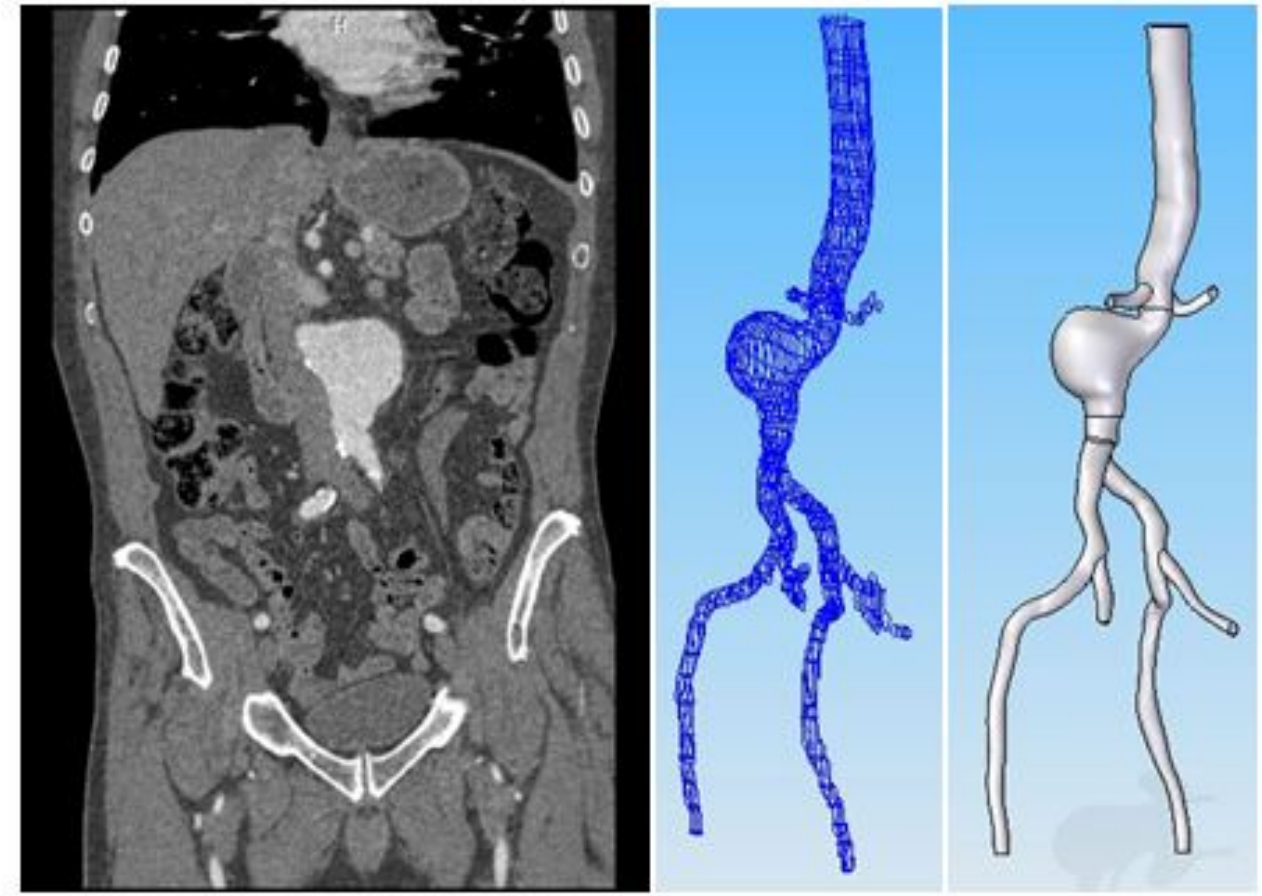
- Realne 3D geometrije rekonstruisane su uz pomoć *Computer Aided Design (CAD)* softvera *Solid Edge v20.*

- Pacijent 1



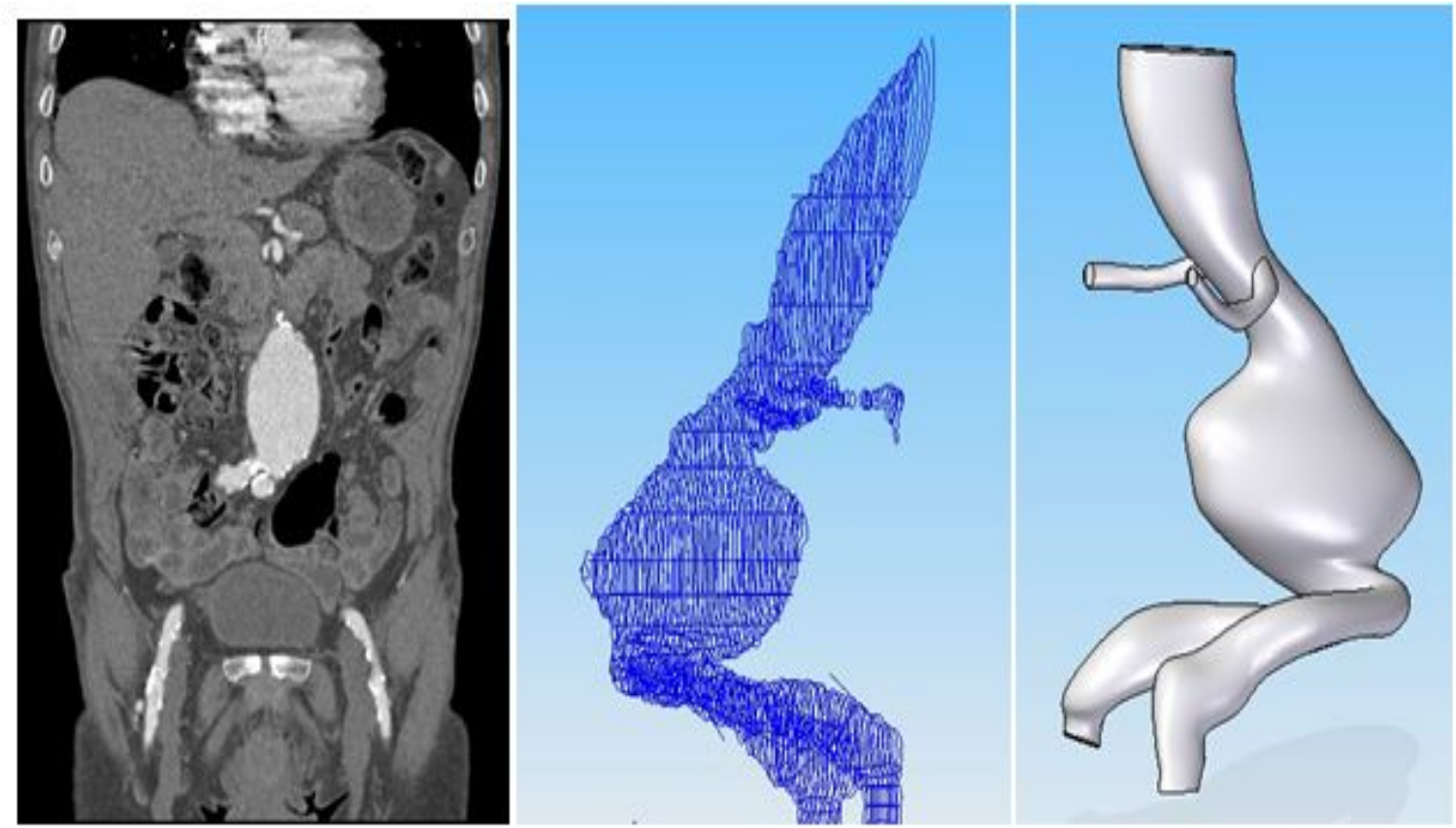
Metode-Rekonstrukcija 3D geometrije

- Pacijent 2



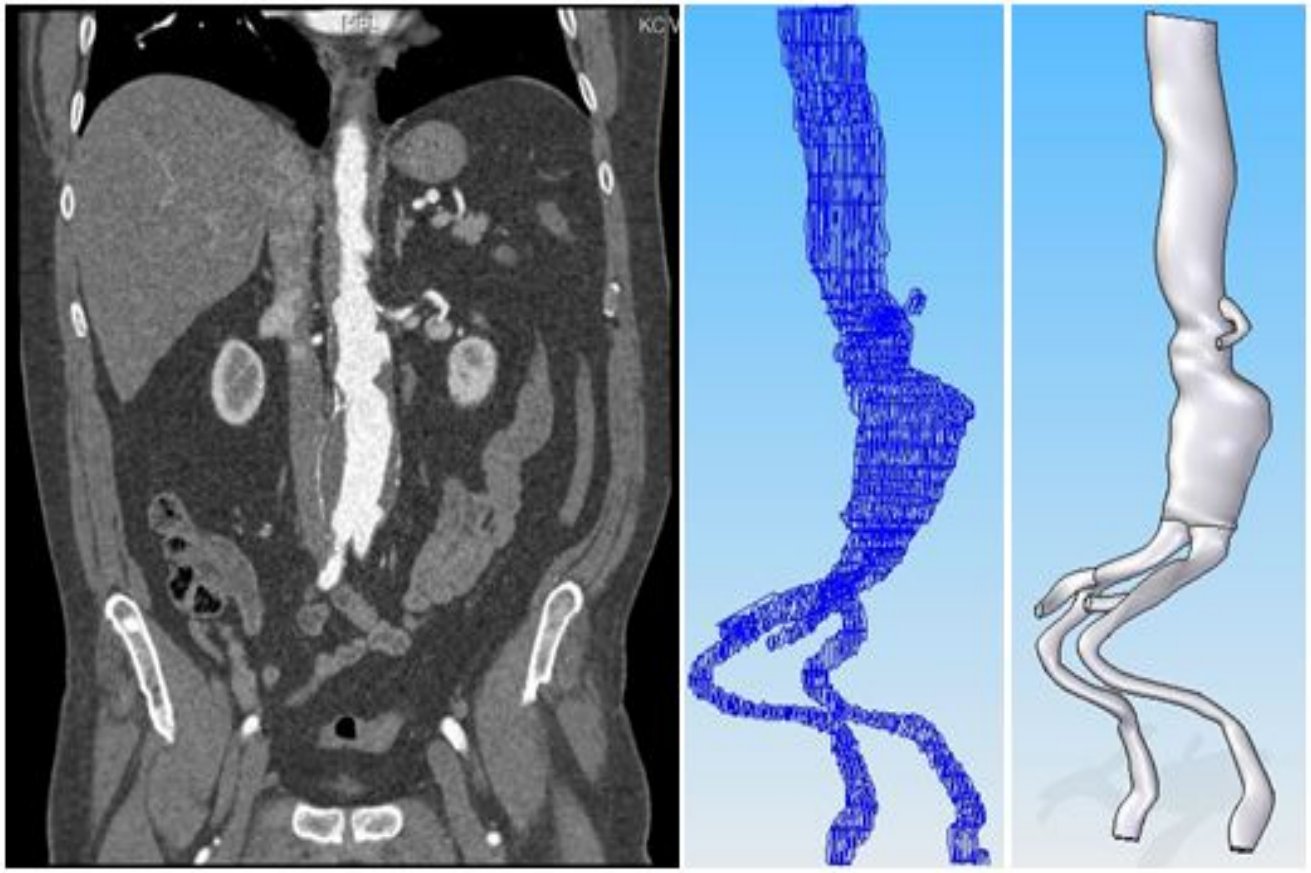
Metode-Rekonstrukcija 3D geometrije

- Pacijent 3



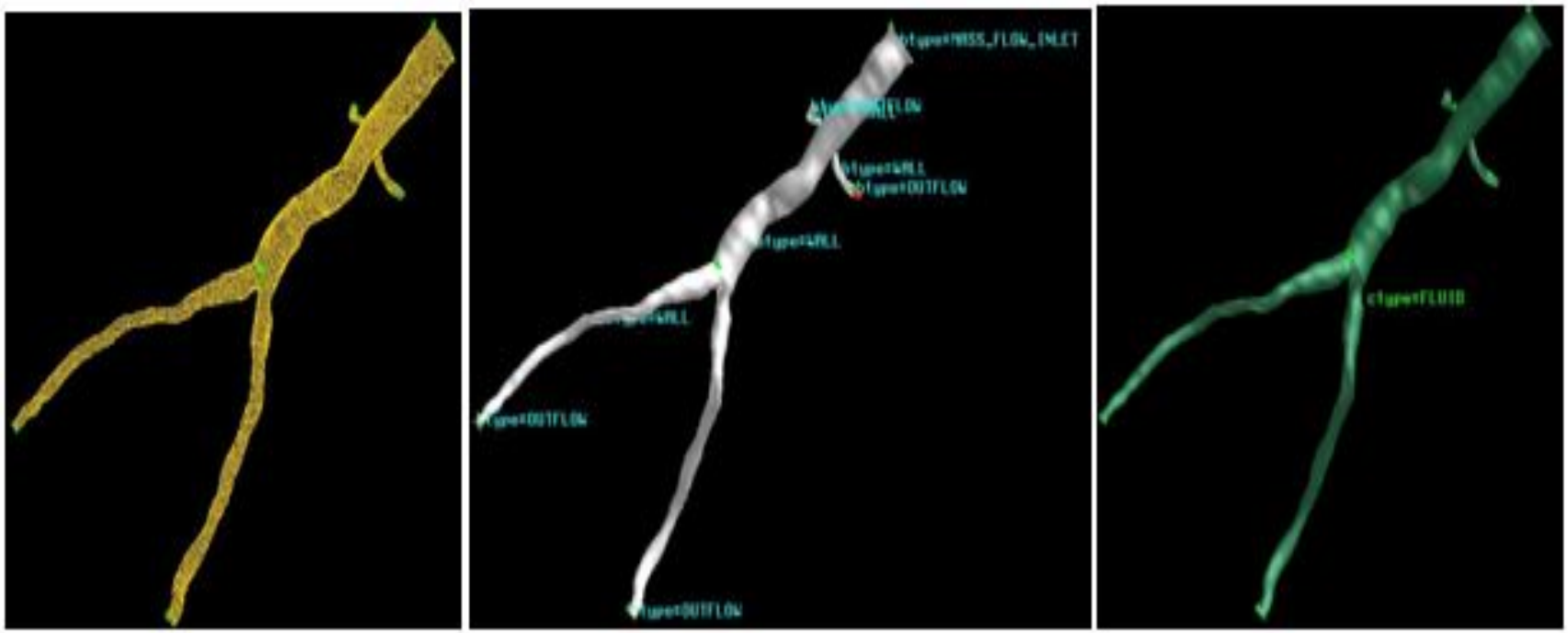
Metode-Rekonstrukcija 3D geometrije

- Pacijent 4



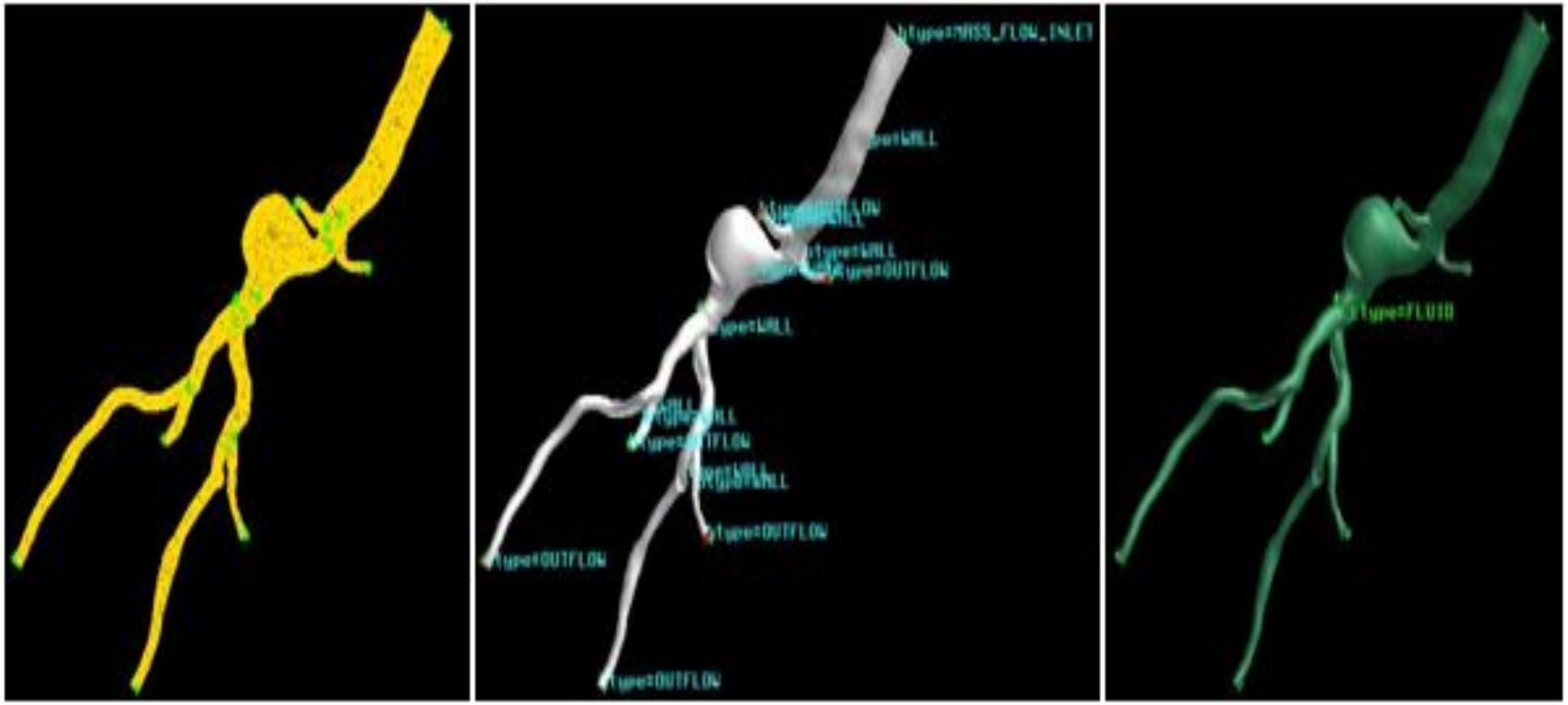
Metode-Stvaranje mreže i diskretizacija

- Softver *Ansys Gambit 2.4* je korišćen stvaranje mreže, diskretizaciju, definisanje graničnih zona i zone kontinuuma.
- Pacijent 1



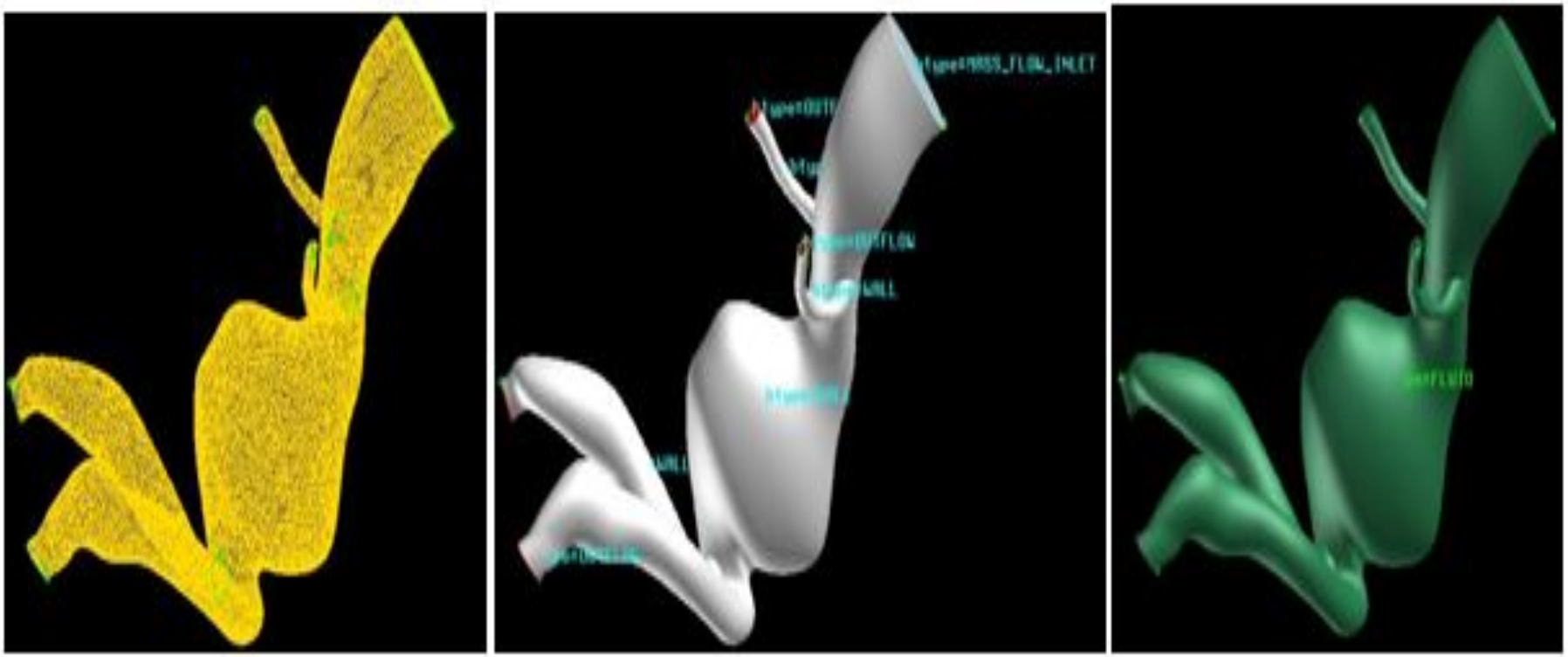
Metode-Stvaranje mreže i diskretizacija

- Pacijent 2



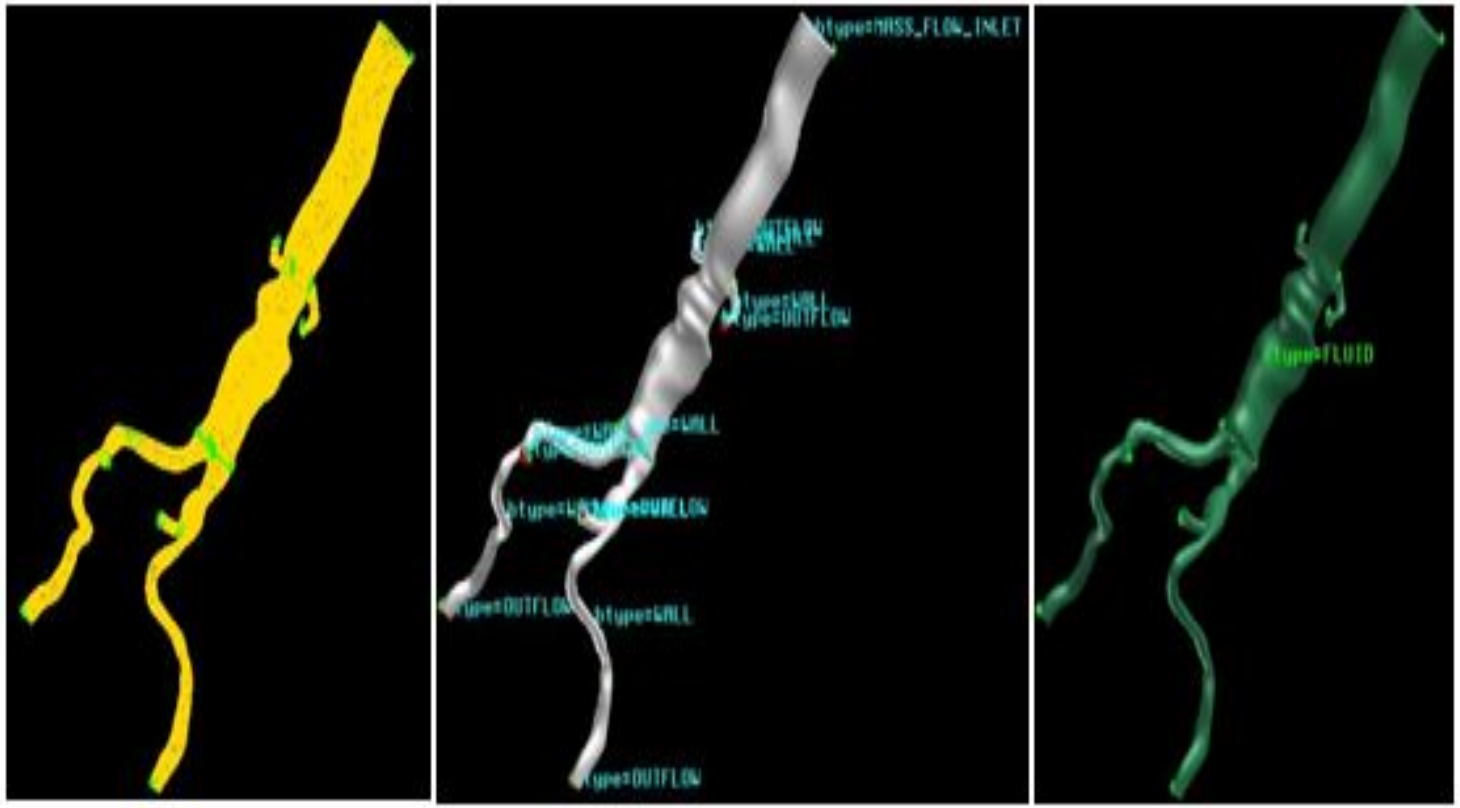
Metode-Stvaranje mreže i diskretizacija

- Pacijent 3



Metode-Stvaranje mreže i diskretizacija

- Pacijent 4



Metode-Simulacije u stacionarnom stanju

- Pretpostavka: krv homogen, nestišljiv nenjutnovski fluid; zidovi krvnog suda rigidni; primenjeno je stanje bez klizanja.
- Softver *Ansys Fluent 13.0*
- Reynolds stress model
- *Non-Newtonian Power law (krv)*

$$\eta = k\dot{\gamma}^{n-1}e^{T_0/T}$$

$$\eta_{min} < \eta = k\dot{\gamma}^{n-1}e^{T_0/T} < \eta_{max}$$

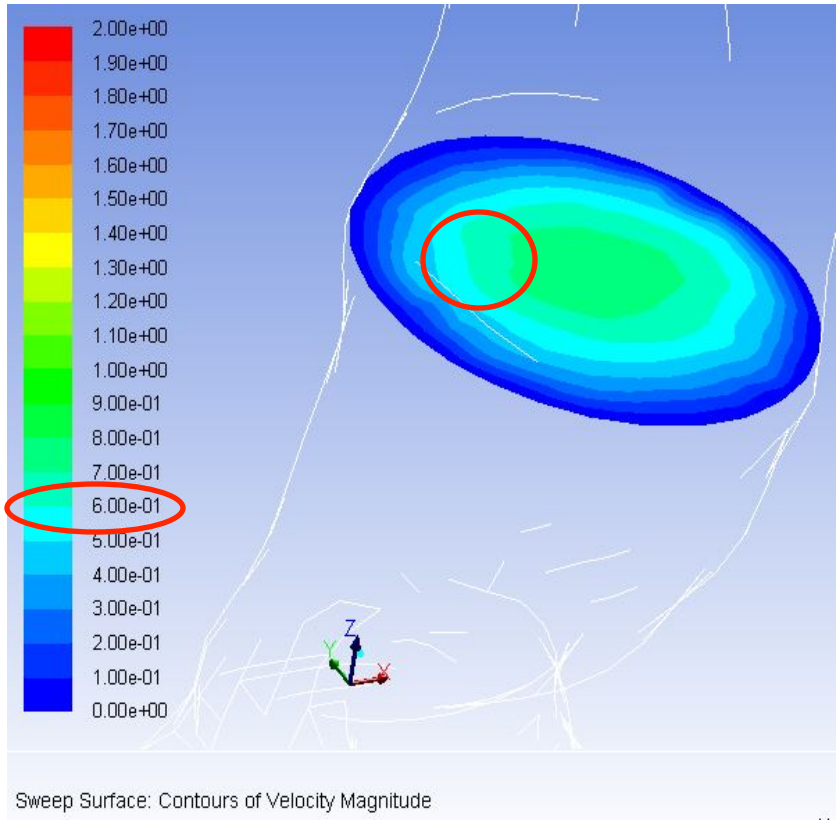
Parameters	Description of Parameters
Viscosity Lower Limit η_{min}	0.00125 kg/ms
Viscosity Higher Limit η_{max}	0.00300 kg/ms
Power law Index n	0.48510
Consistency Index k	0.20730 kgs^{n-2}/m
Reference Temperature T_0	310 K

Rezultati

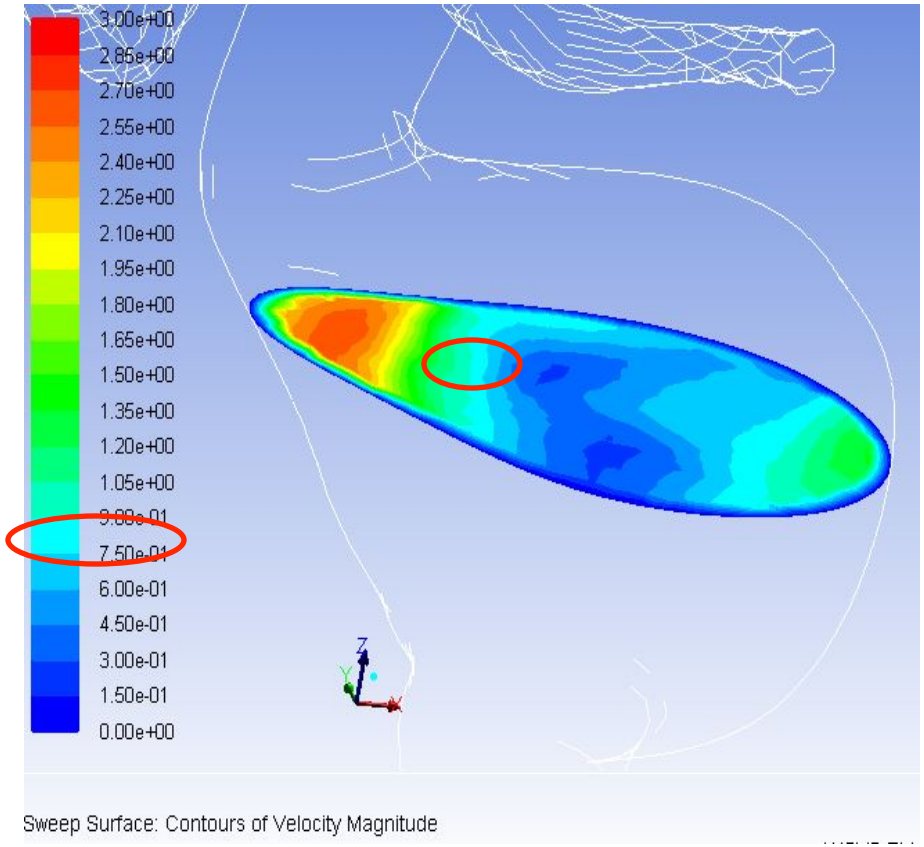
										Aneurizma		
Pacijent		Inlet	LR	RR	LI	RI	LII	RII	Dopler	Pre	U	Posle
1	v [m/s]	1,1	3,6	2,5	2,25	2,25	/	/	0,61	1	0,6	0,9
	P [kPa]	26,4	126	44,3	6,89	2,76	/	/	/	26,2	24,8	23,4
2	v [m/s]	2,1	0,6	2,7	3	3	3,3	3	0,80	2,25	0,8	1,5
	P [kPa]	35	12,4	4,12	10,3	8,23	16,5	12,4	/	32,4	26,8	28,8
3	v [m/s]	2,5	9	9	3,75	2,75	/	/	0,78	2,25	0,7	1
	P [kPa]	16,6	2,93	2,93	1,95	8,76	/	/	/	13,7	11,7	12,7
4	v [m/s]	1	2,75	2,5	1,1	1,1	2,5	2,25	0,49	1	0,5	0,9
	P [kPa]	20,8	4,16	6,24	2,08	4,16	10,4	10,4	/	19,7	19,7	18,7

Rezultati-konture brzine

Pacijent 1

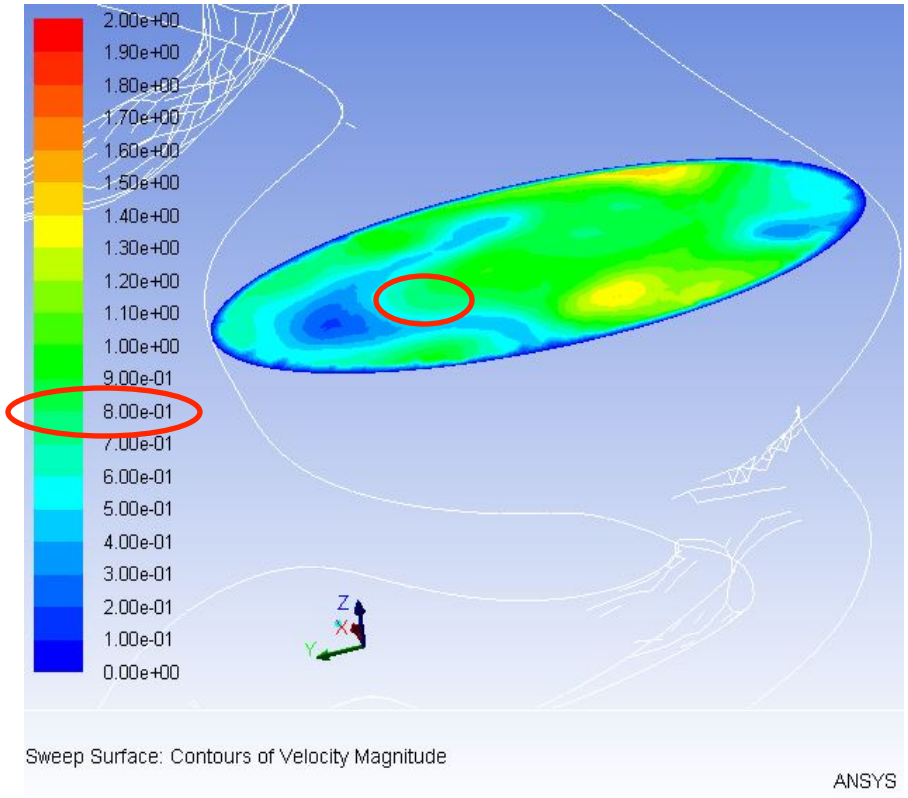


Pacijent 2

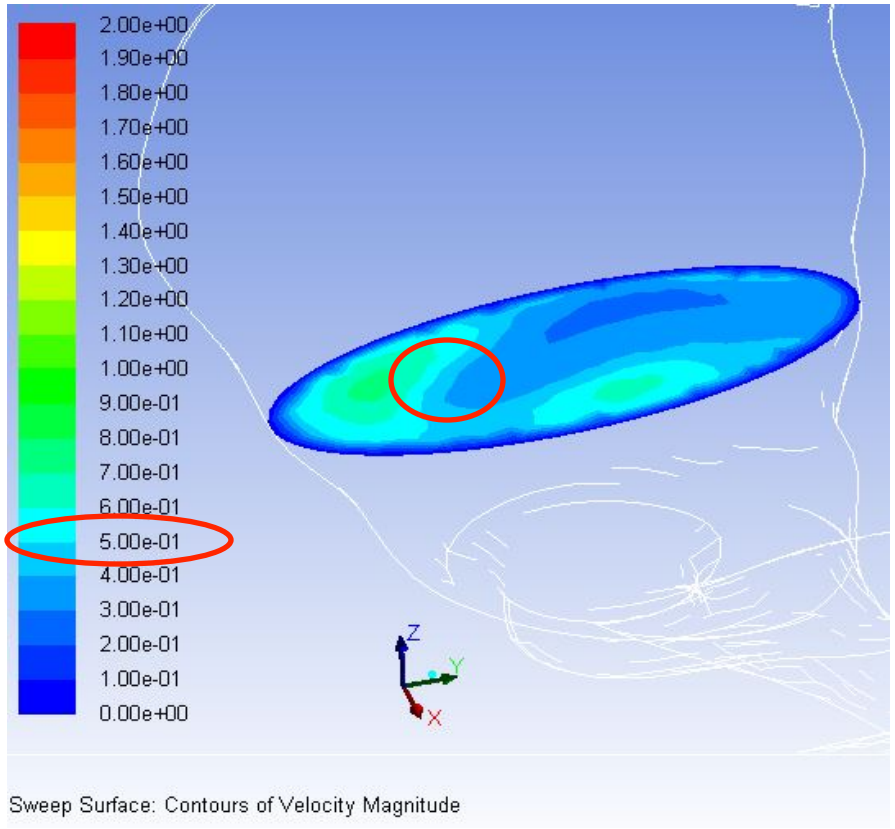


Rezultati-konture brzine [m/s]

Pacijent 3

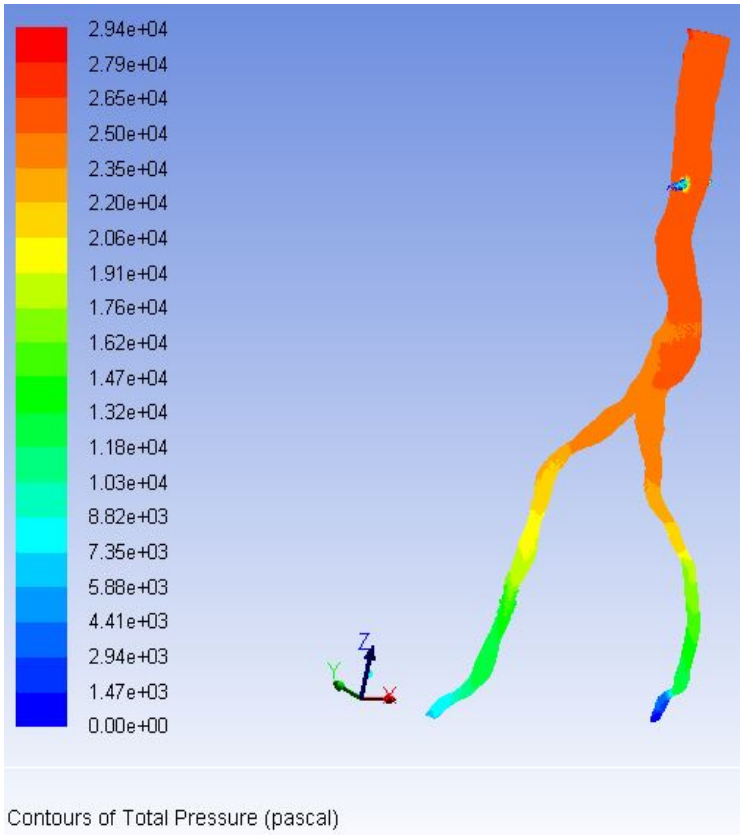


Pacijent 4

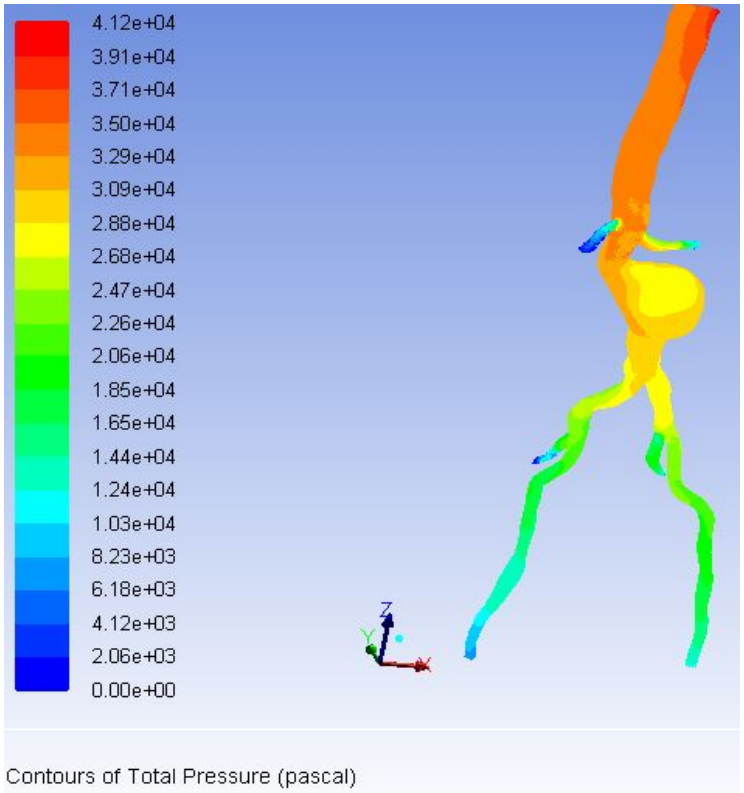


Rezultati-konture totalnog pritiska [Pa]

Pacijent 1

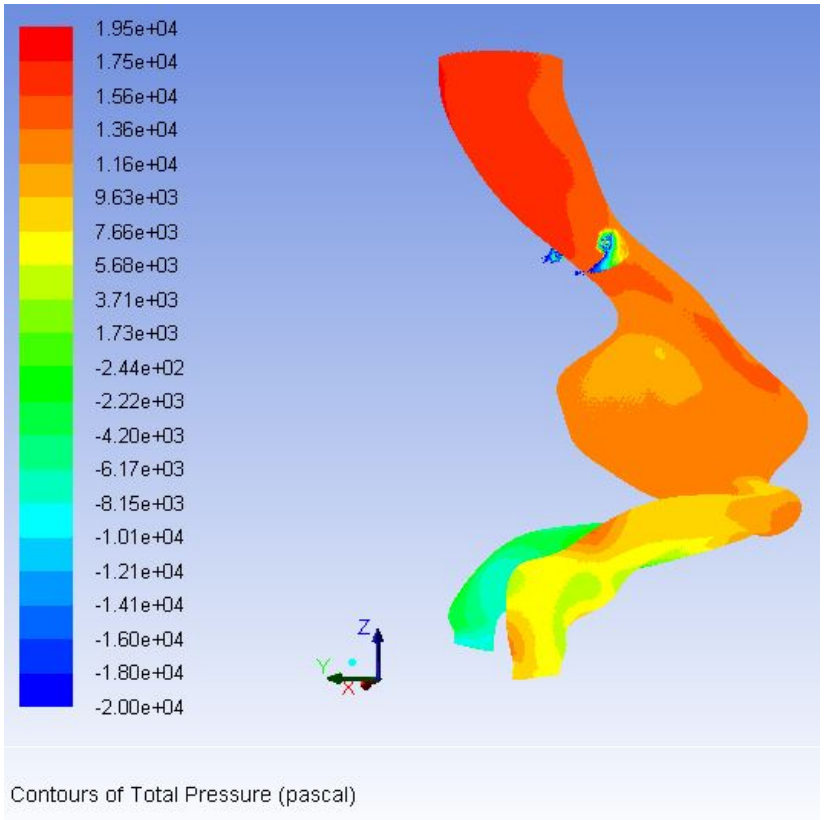


Pacijent 2



Rezultati-konture totalnog pritiska [Pa]

Pacijent 3



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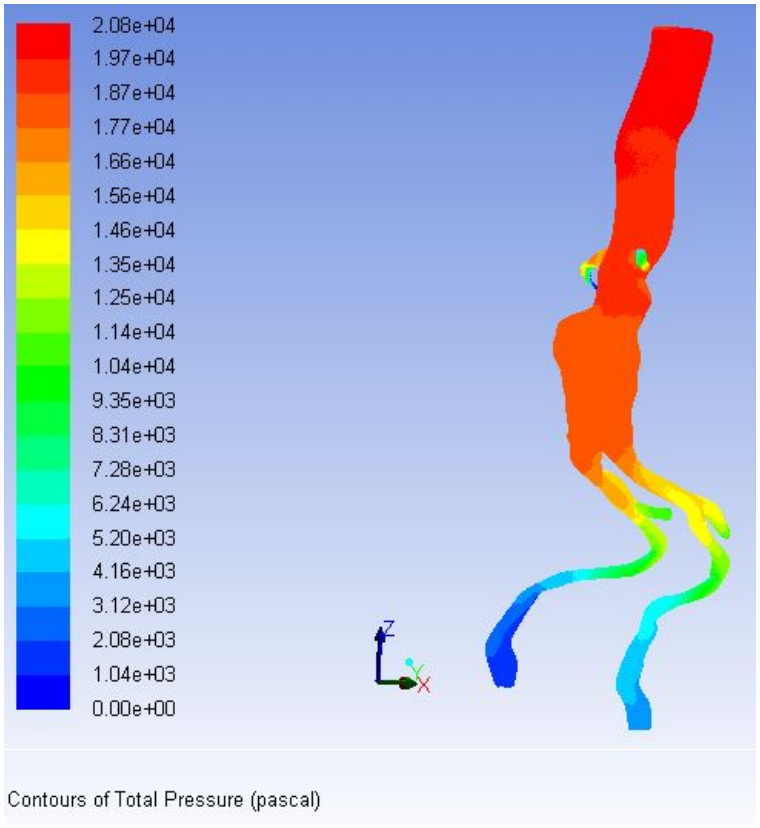
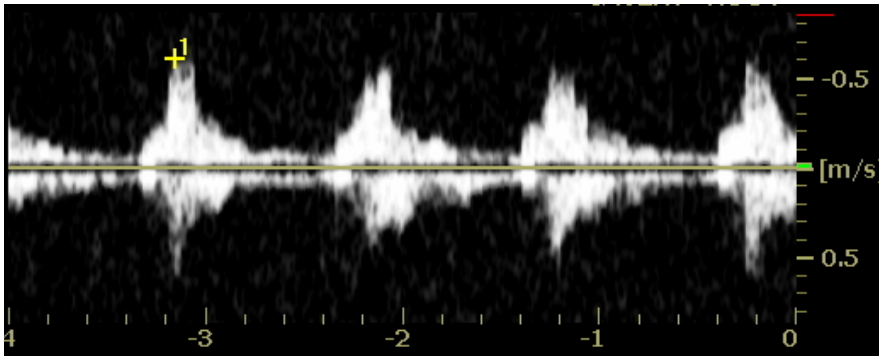
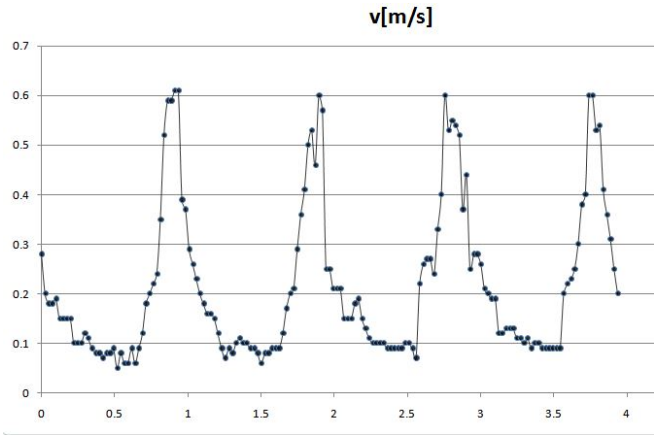


Dinamičke simulacije

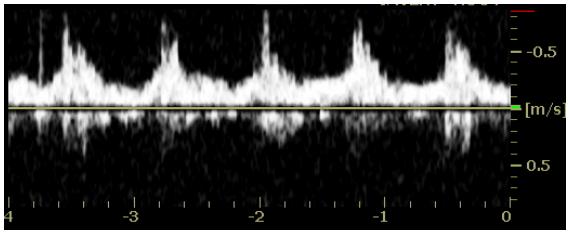
- Progra**m**:*Solid Works 2012*
- Zid aorte: linearno elastičan izotropan materijal
- Krv: model iz *Solid Works-a* i Non-Newtonian Power law
- Pulsni protok krvi rekonstruisan na osnovu Doplerovog spektra, softver GetData

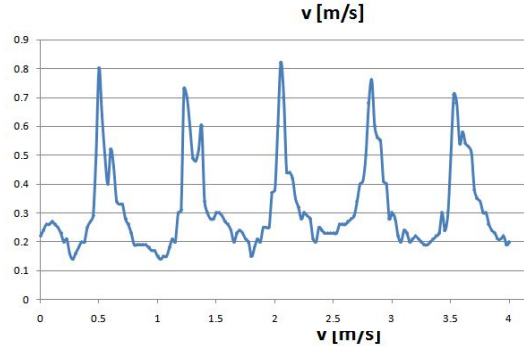
Pacijent 1



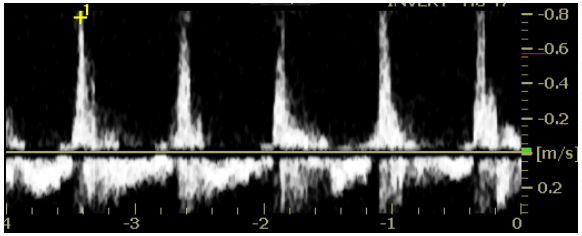


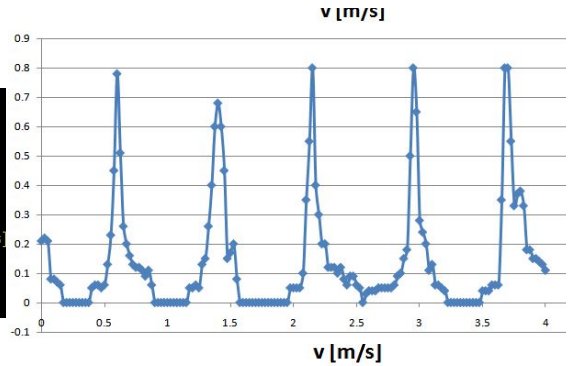
Dinamičke simulacije



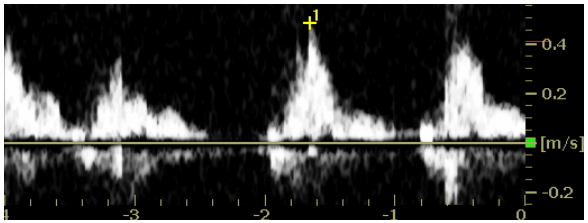


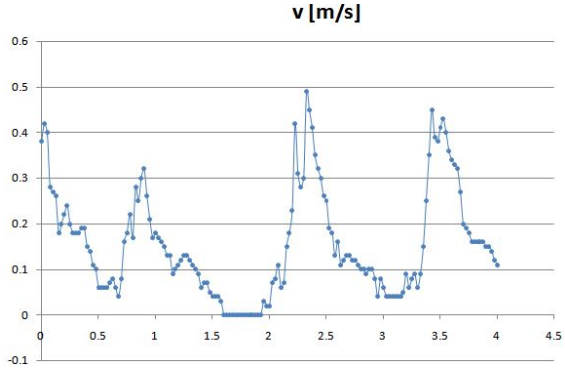
Pacijent 2





Pacijent 3



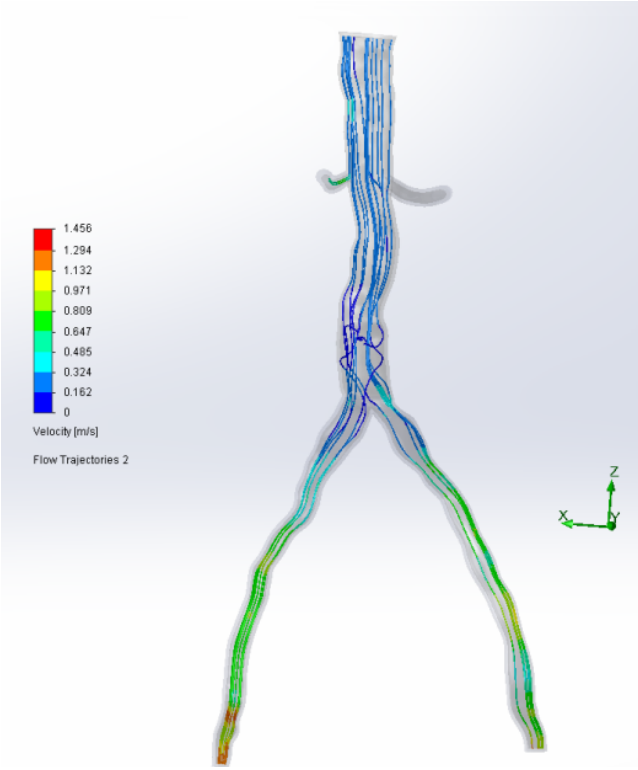


Pacijent 4

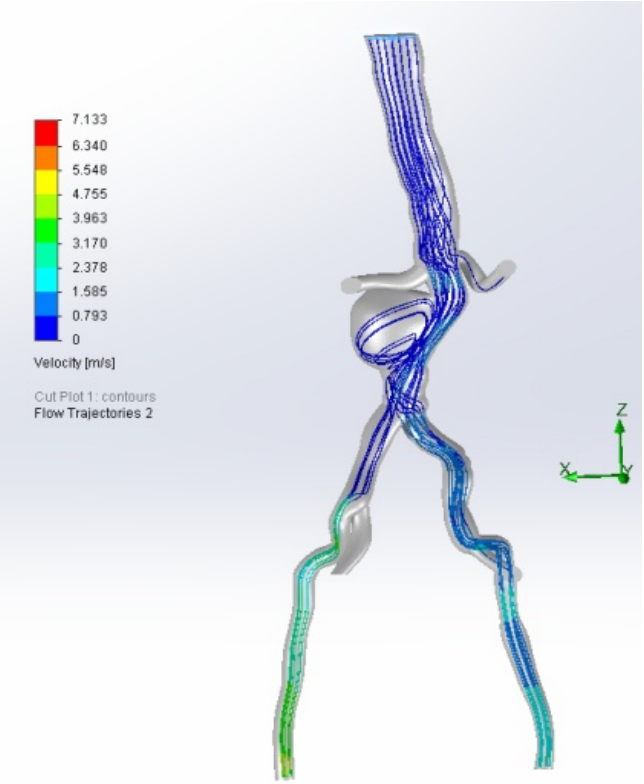
Dinamičke simulacije-Rezultati

- Trajektorija brzine

Pacijent 1



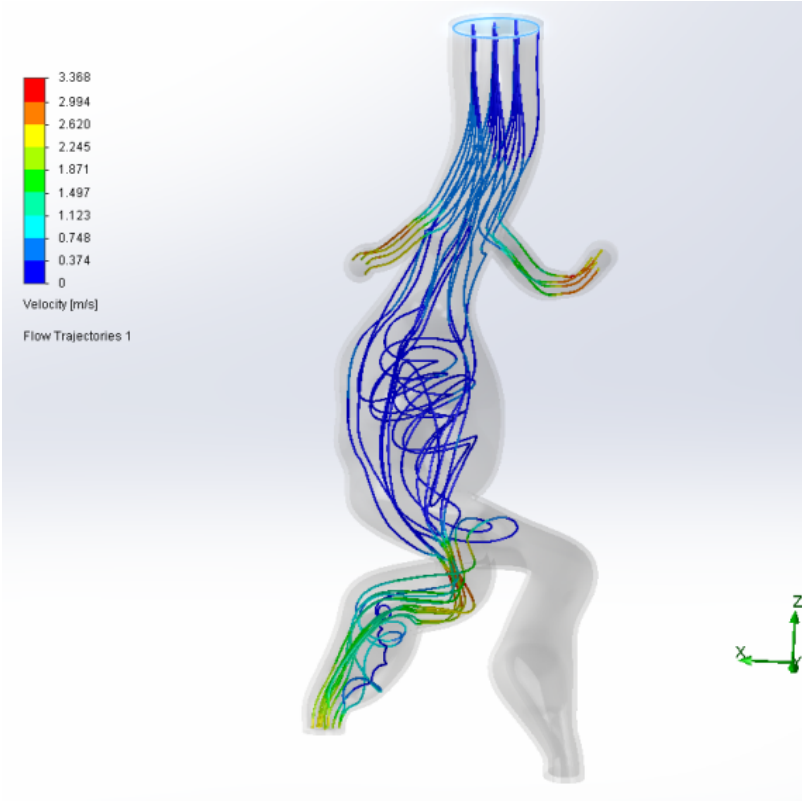
Pacijent 2



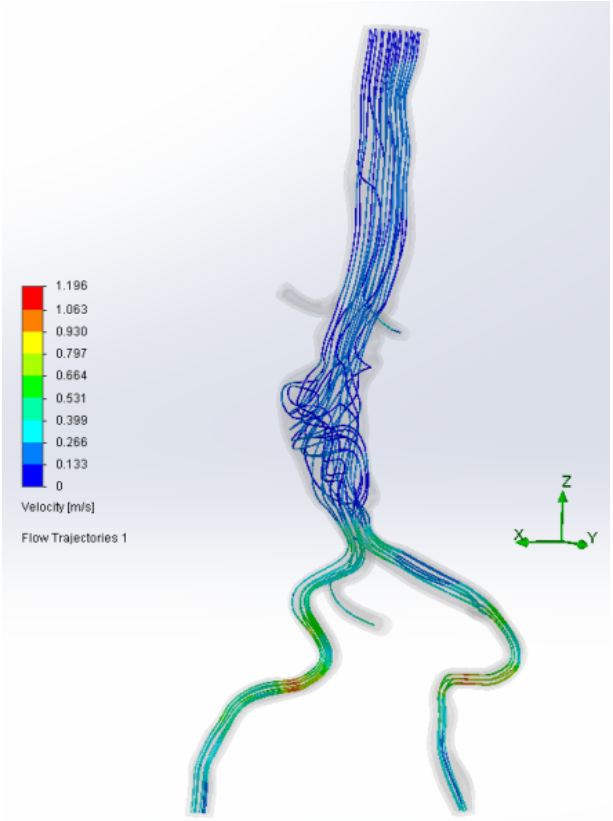
Dinamičke simulacije-Rezultati

- Trajektorija brzine

Pacijent 3

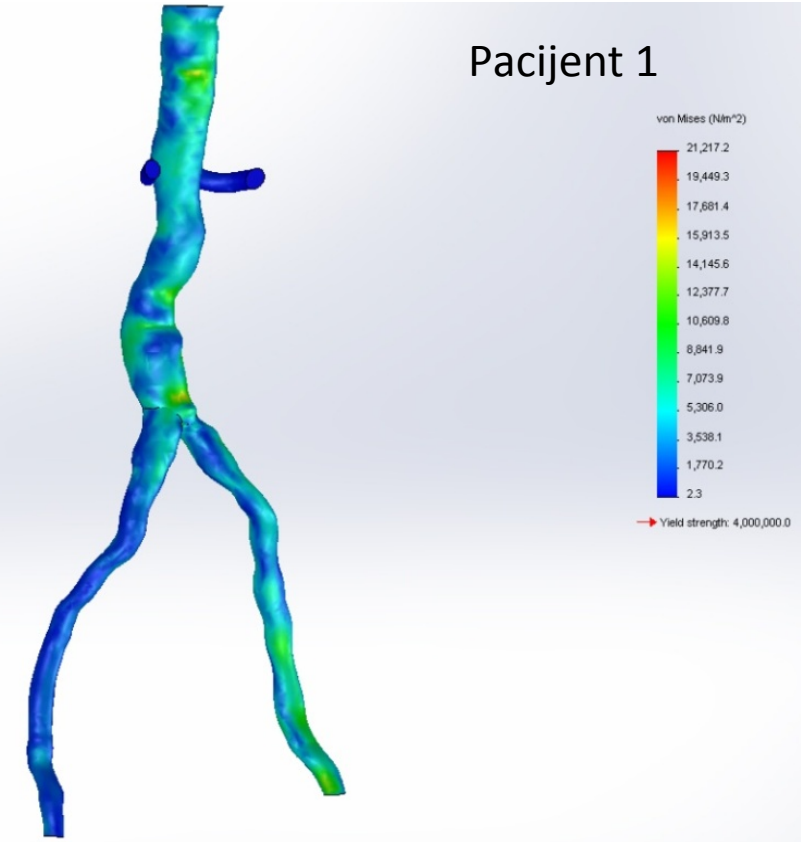


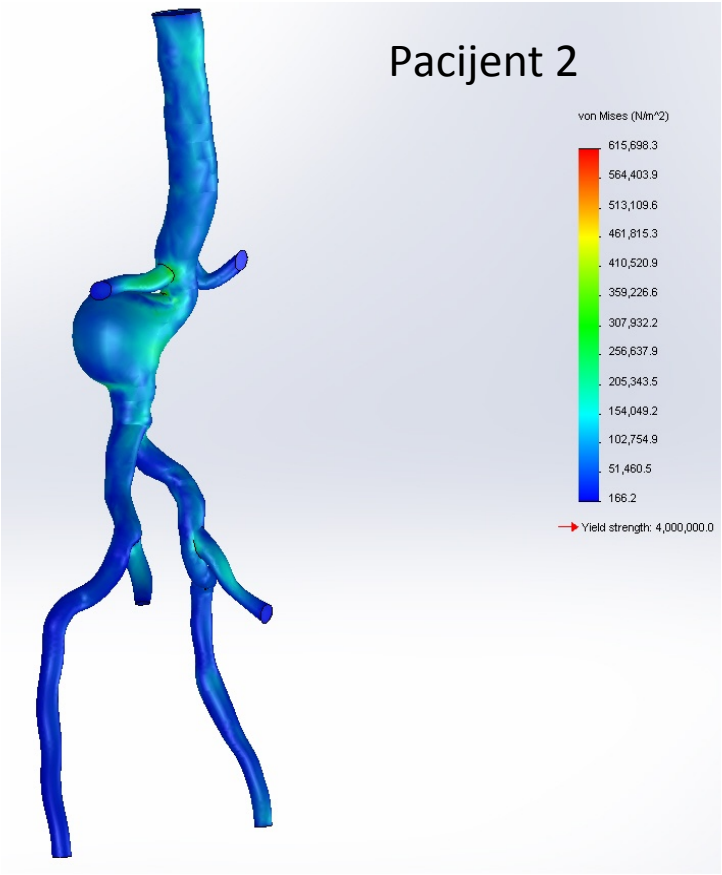
Pacijent 4



Dinamičke simulacije-Rezultati

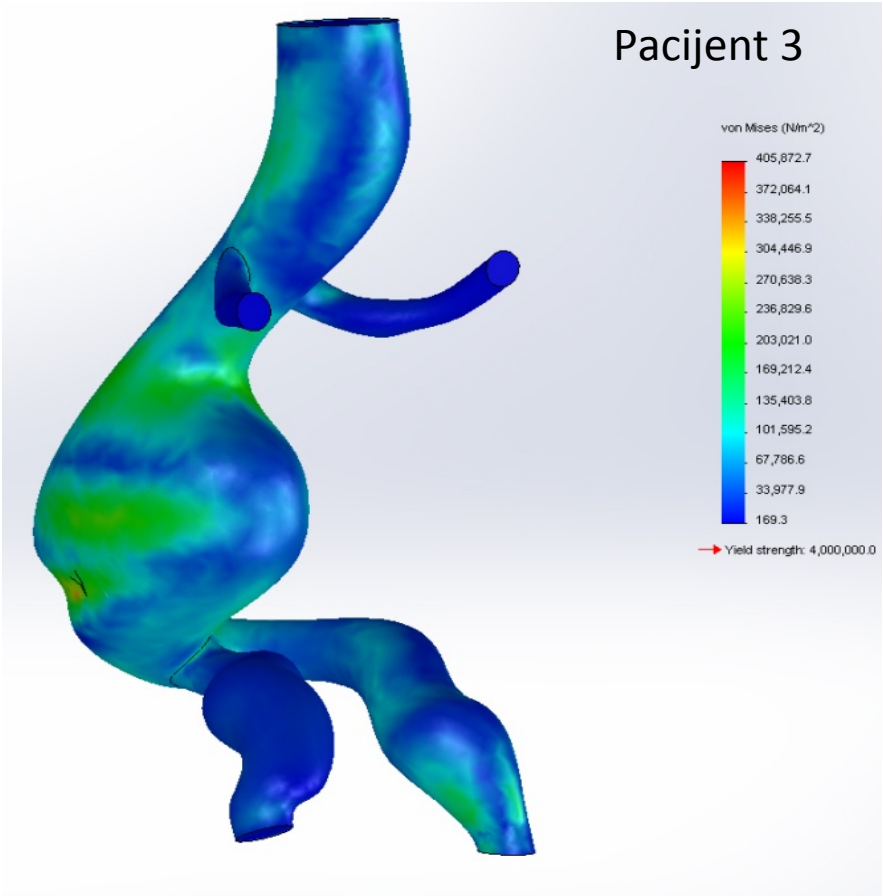
- Distribucija napona!!!

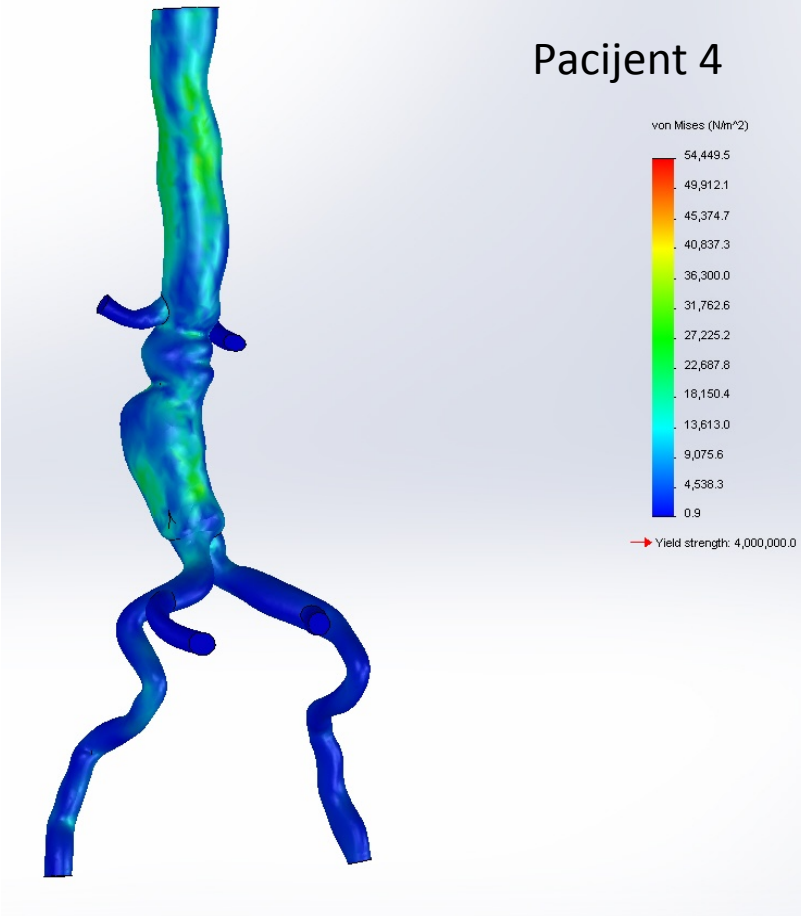




Dinamičke simulacije-Rezultati

- Distribucija napona !!!





Diskusija

- I u stacionarnim i dinamičkim simulacijama dobre vrednosti brzine- možemo reći da je naš model dobar!
- U mogućnosti smo da dobijemo i parametre koji se ne mogu meriti n**e**invazivno!
- Kategorizacija (*Fillinger i Raghavan):*

Grupe	**Maksimalan napon na zid AAA [N/m^2]**
Rupture	477000±60000
Emergent symptomatic	475000±40000
Elective repair	369000±20000

Diskusija

- Maksimalan napon nije na mestu najvećeg dijametra, već je češće na posterolateralnoj lokaciji.
- Pacijenti 3 i 4 mala razlika d, velika razlika napona!!!!

	Max. *von Misses* napon [N/m^2]	Maksimalan dijametar [cm]	Kategorija na osnovu maksimalnog napona	Potrebna hirurška intervencija na osnovu maksimalnog dijametra (> 5.5 cm)
Pacijent 1	21217	4,2	Mala verovatnoća rupture	Ne
Pacijent 2	615698	6,0	*Rupture*	Da
Pacijent 3	405873	5,6	*Elective repair*	Da
Pacijent 4	54449	5,4	Mala verovatnoća rupture	Ne

Zaključak

- Neinvazivna metoda!
- Analiza uz pomoć CFD daje veći broj informacija u odnosu na kriterijum maksimalnog dijametra.
- Dobri rezultati pokazuju da smo na dobrom putu, ali je potrebno još mnogo rada da bi ostvarili konačan cilj!

Hvala na pažnji!