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Comparison of nasal anatomies using computational fluid dynamics

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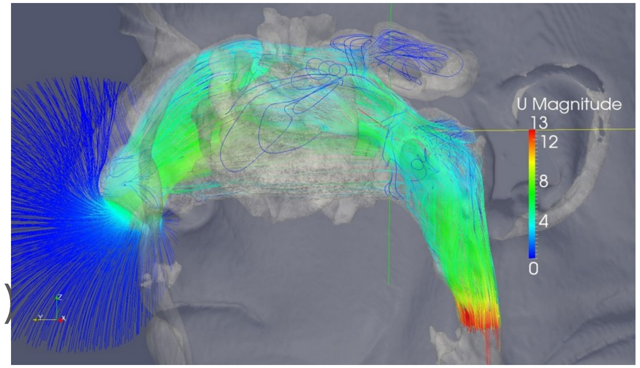
Introduction

- Nasal breathing difficulties (NBD) are as **widespread** and important as **difficult to diagnose**;

- Surgical corrections are often necessary, but the **failure rate is high** (more than 50%) resulting in higher health care costs.

  D. A. Campbell, M. G. Moghaddam, J. S. Rhee, and G. J. M. Garcia.
  Narrowed Posterior Nasal Airway Limits Efficacy of Anterior Septoplasty. 2021

Introduction - OpenNOSE



- The OpenNose community is active

  since 2011 and a Website (www.open-nose.org)

  will be launched in 2023;
- Multidisciplinary community (~30 people) and PoliMi (Milan, Italy) is the group leader.
- It's driven by clinical problems and ENT surgeons are integral part of the group;
- It aims at developing virtual surgeries to give support to surgeons by evaluating different virtual operations before the real one.
- This project will foster the emerging community of Computational Rhinology.
- DNS, experimental and anatomy data will be freely available to anyone to create a standard.

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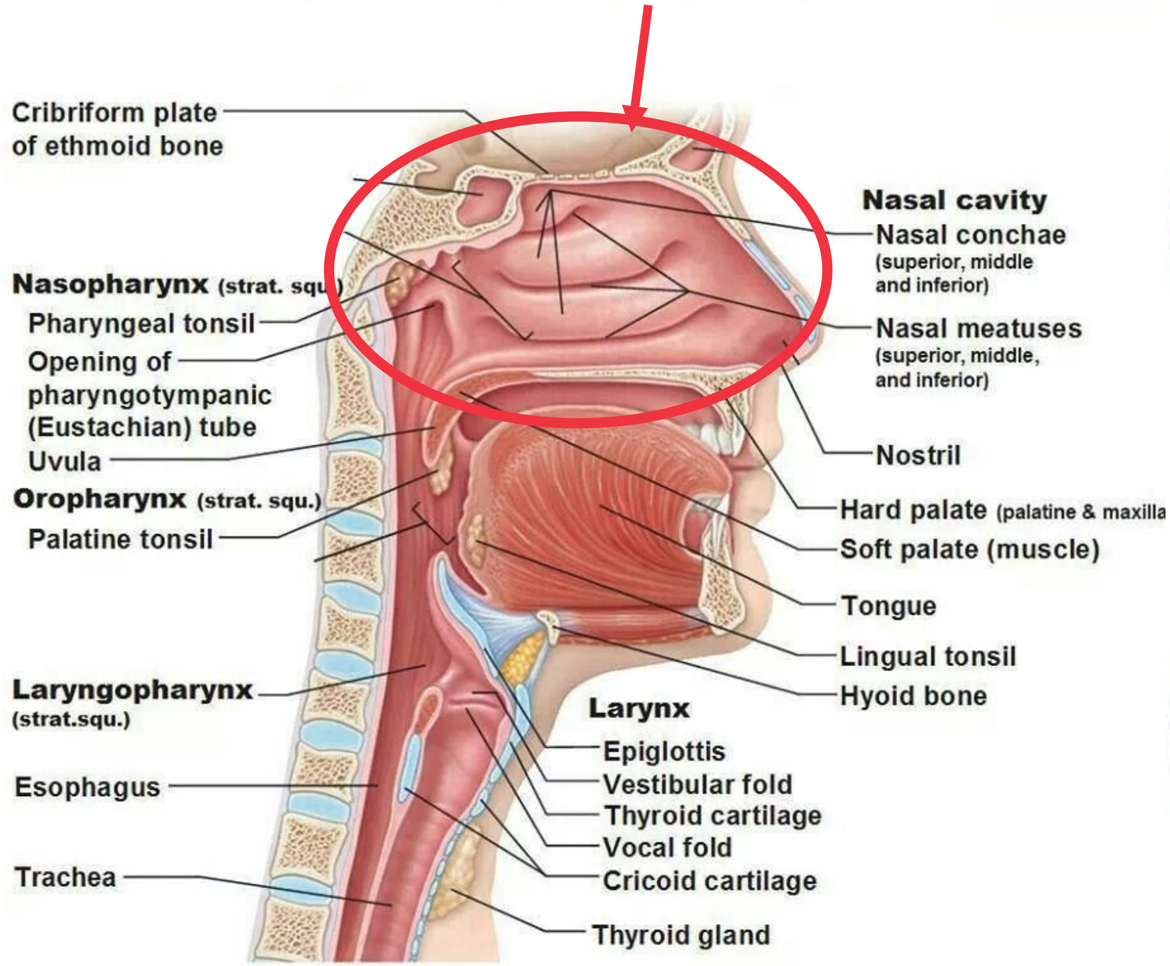
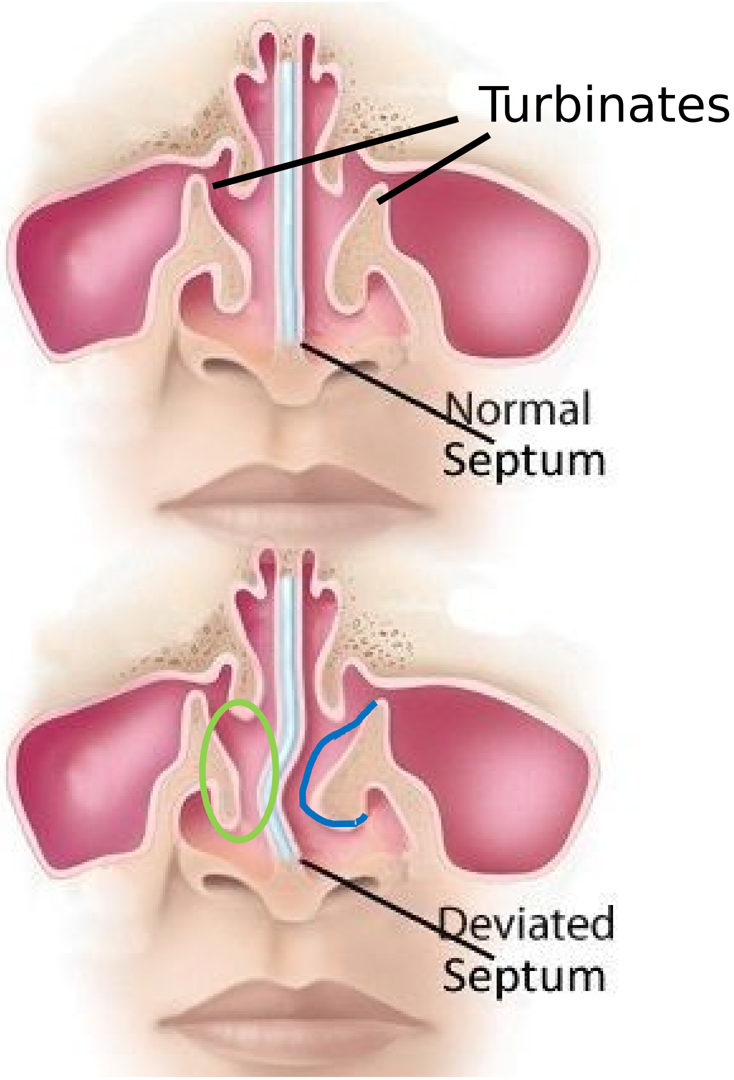
Some background.

Medical background

Deviated septum

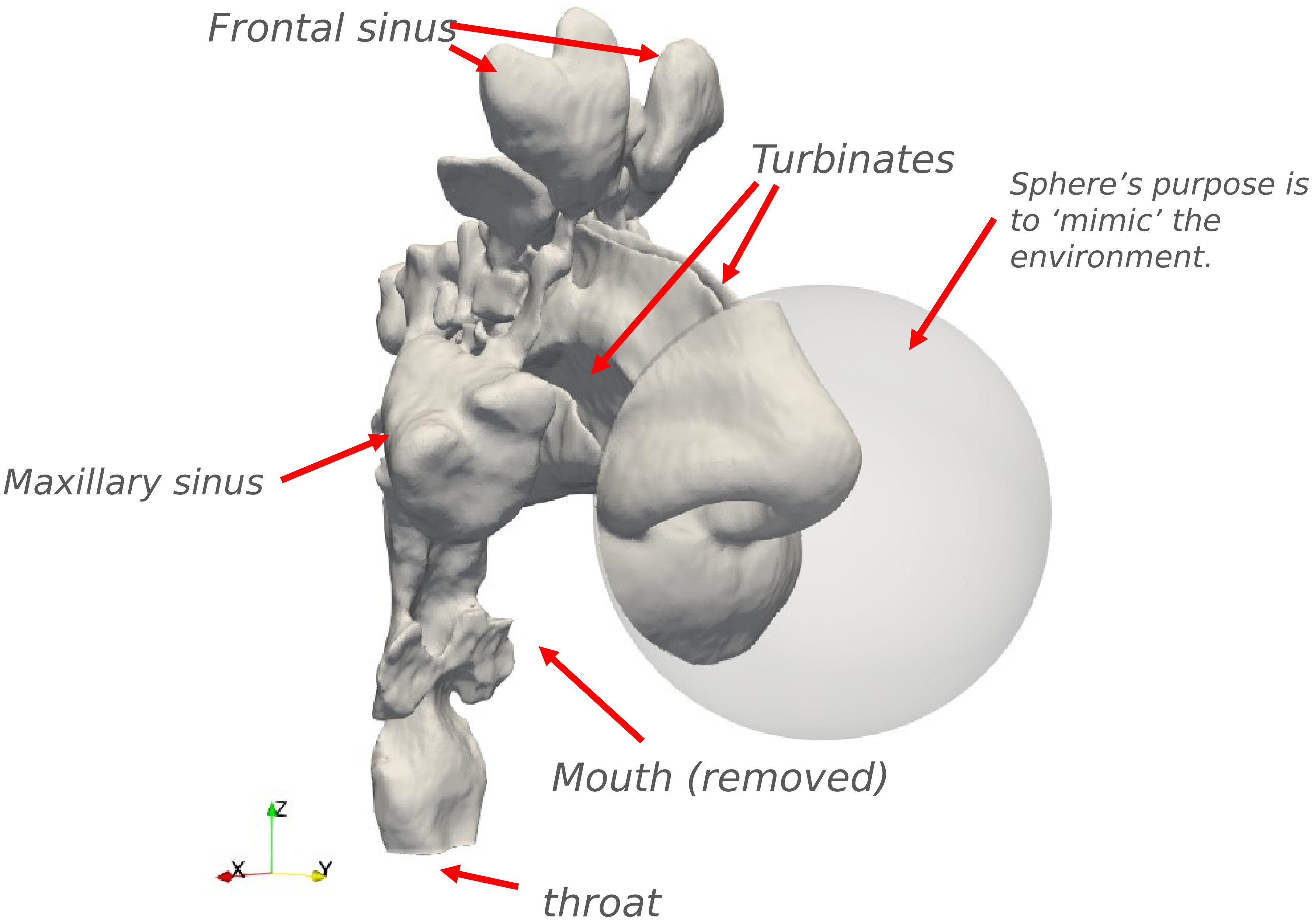




Reduction of the area where air can flow, in a nostril

Hypertrophy of the turbinate of the other nostril

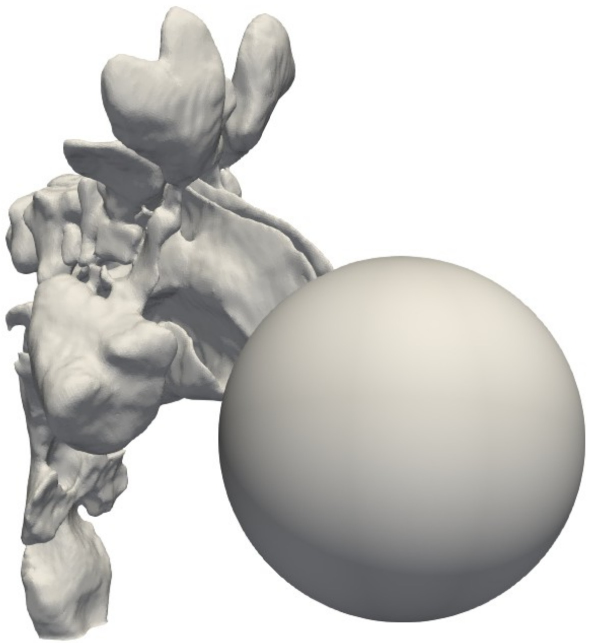
Pre-surgery anatomy

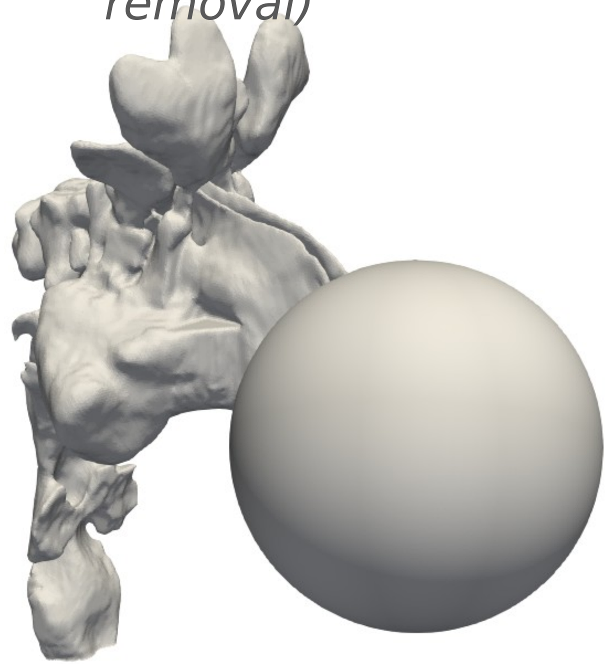


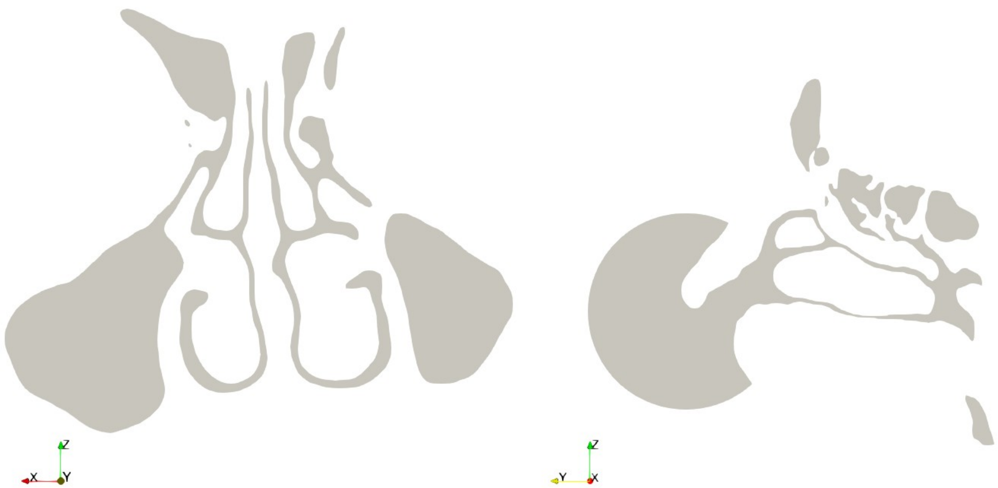
Virtual surgery effect

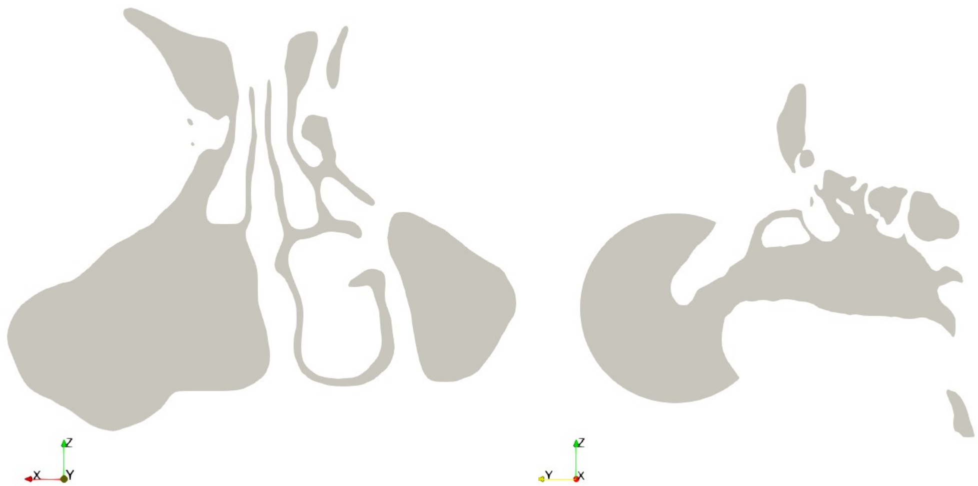
before the surgery

after maxillectomy (maxillary sinus removal)









Open questions

Some of the open questions which we are working on:

1. Which numerical model makes the comparison more realistic, especially when comparing pre- and post-op;
2. How to measure well-being of a patient;
3. How to compare well-being before and after the surgery;
4. How to properly share the results with surgeons.
5. …

Open questions

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5. …

First question

FLOW CONTROL FOR TURBULENT DRAG REDUCTION ⟷ *FLOW CONTROL FOR NBD CORRECTION*

- The analogy can be made due to previous experience with flow control.
- In both cases the flow is manipulated and it must be compared before and after the application of control.
- The application of control alters the natural state of flow.

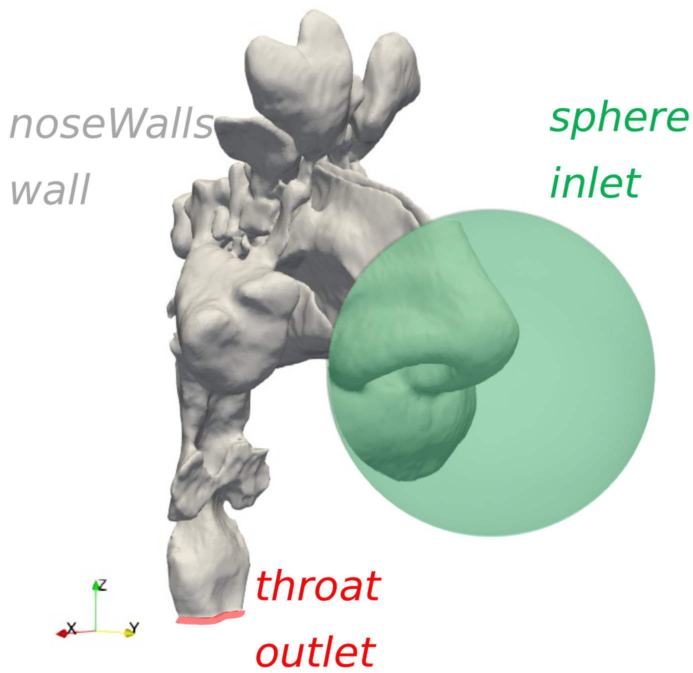
First question

*FLOW CONTROL
FOR TURBULENT
DRAG REDUCTION* ⟷ *FLOW CONTROL
FOR NBD
CORRECTION*

To compare pre- and post- surgery anatomies we can apply the following boundary conditions:

- **Constant Pressure** ;
- **Constant Flow Rate** ;
- **Constant Power Input**

Hasegawa, Quadrio, Frohnapfel, J. Fluid Mech. (2014)

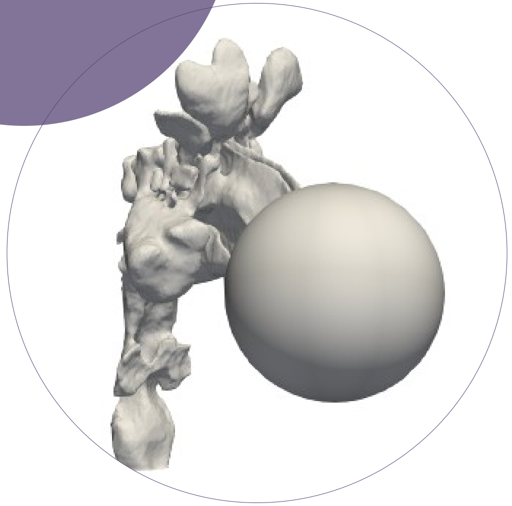


Workflow: CT Scan to Numerical Solution

CT scan of patient's head.

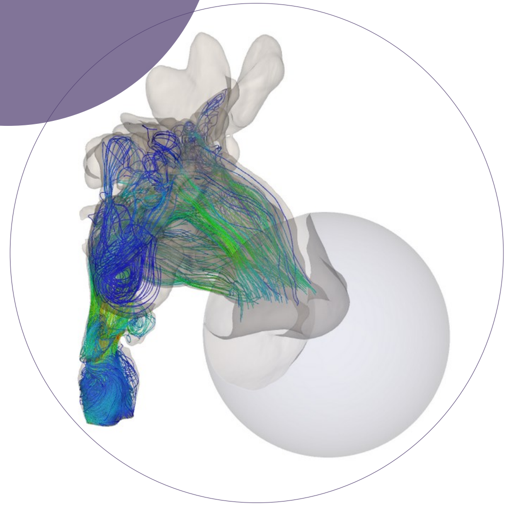
- *3D slicer: used to create geometry*
- *STL file: obtained from an hospital based in Milan.*

Upper airways extraction.



- *Hounsfield Unit (HU)*
- *Interaction with Medical Doctors important to create realistic geometry.*

Simulation of its airflow.



- *LES – WALE model*
- *Unsteady Transitional flow*

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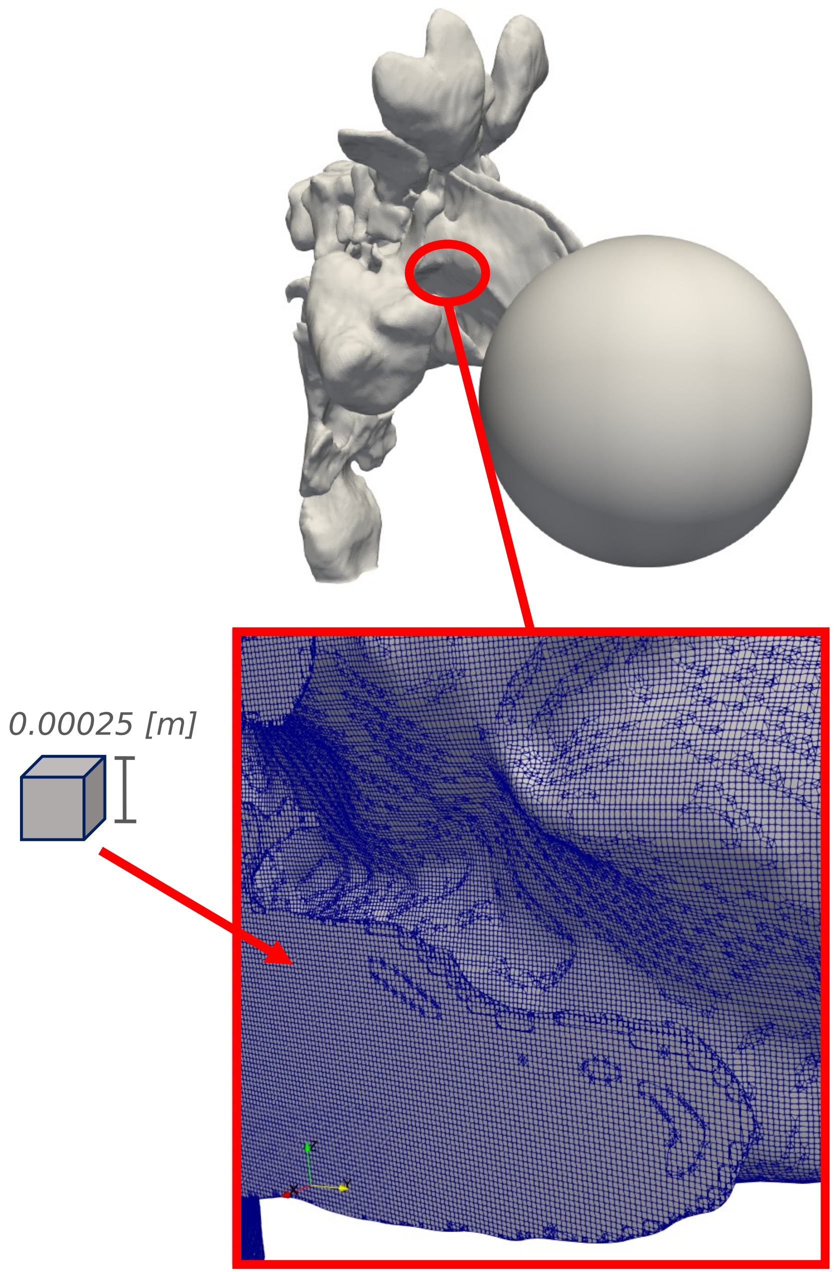
Meshing.

Meshing



Mesh stats:

Cells ~ 15000000

of which:

Hexahedra ~ 14500000

Prisms ~ 50000

Wedges: 0

Pyramids: 0

Tet wedges: ~ 22

Tetrahedra: 0

Polyhedra: ~ 175000

Mesh quality:

Non-otho: Max: ~ 60 , average: ~ 4

Max skewness: ~ 3

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Numerical schemes and solver.

fvSchemes & fvSolution

ddtSchemes: backward

gradSchemes: **G**auss linear

divSchemes: default Gauss linear

laplacianSchemes: Gauss linear limited 0.777

interpolationSchemes: linear

snGradSchemes: limited 0.777

fluxRequired: no

wallDist: method meshWave

solvers

p

—solver: GAMG

—tolerance: 1e-5

—smoother: DICGaussSeidel

U

—solver: smoothSolver

—smoother: symGaussSeidel

PIMPLE

momentumPredictor: yes

nOuterCorrectors: 1

nCorrectors: 2

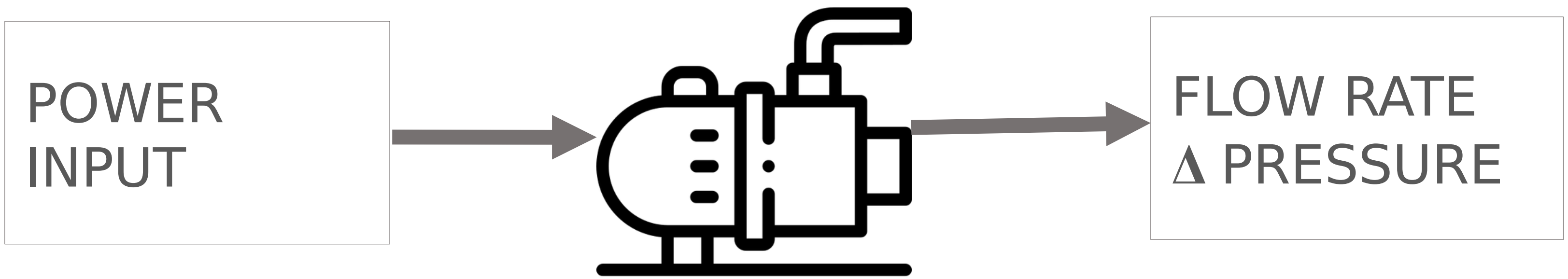
nNonOrthogonalCorrectors: 1

relaxationFactors: fields & eqns to 0.9

Constant Power Input setup.

Boundary condition explained

- Constant Power Input boundary condition is typical for pumps where a certain power comes from the shaft and pressure gradient and flowrate comes after that.



- The boundary condition was implemented in the ESI version using *swak4foam* which allowed us to write a clean, straightforward and readable code.

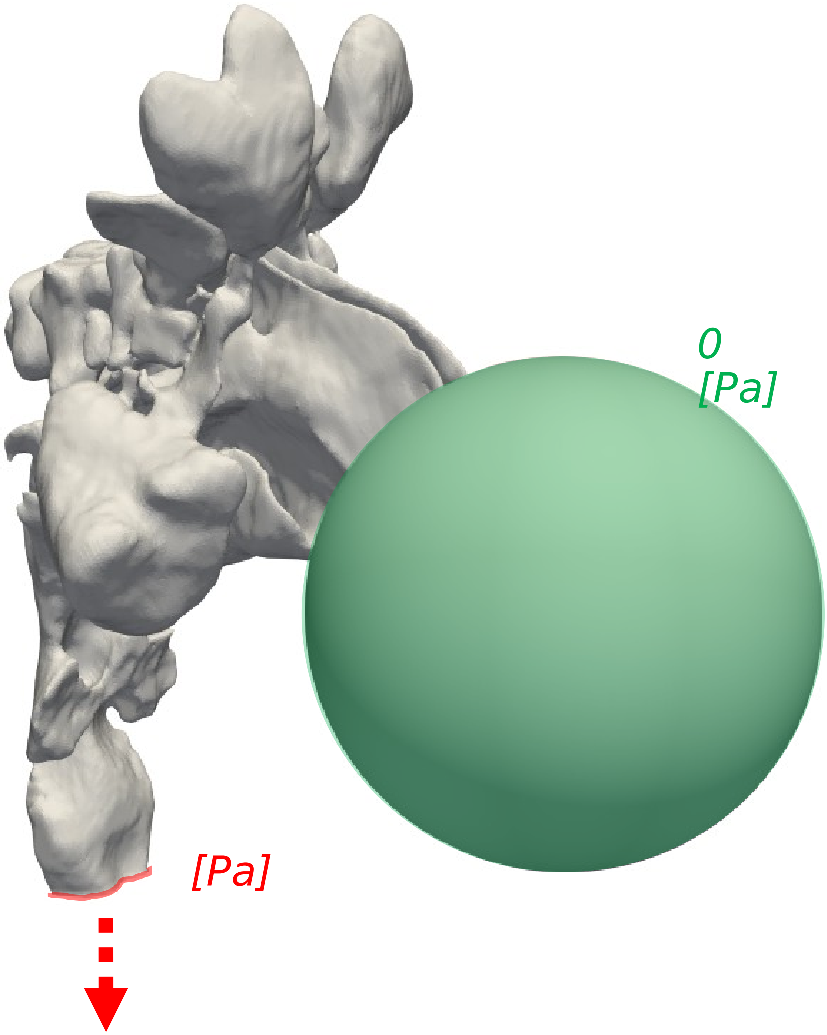
Implementation

- Power Input boundary condition is expressed as:

- The boundary condition was written as follows:

```
throat
{
type  groovyBC;
variables
(
"CPI=-0.00533";
"Qdot=sum(phi)";
);
valueExpression "CPI/Qdot";
value uniform -20;
}
```

Implementation



1. **Initial guess** for pressure is the result of previous calculations.

2. then, with this value of pressure, **a timestep is run** and a certain **flowrate will be calculated** on the throat.

3. This flowrate, by using the expression of the **power input**, gives us a new estimate for the throat pressure and, with that, the loop restarts.

...

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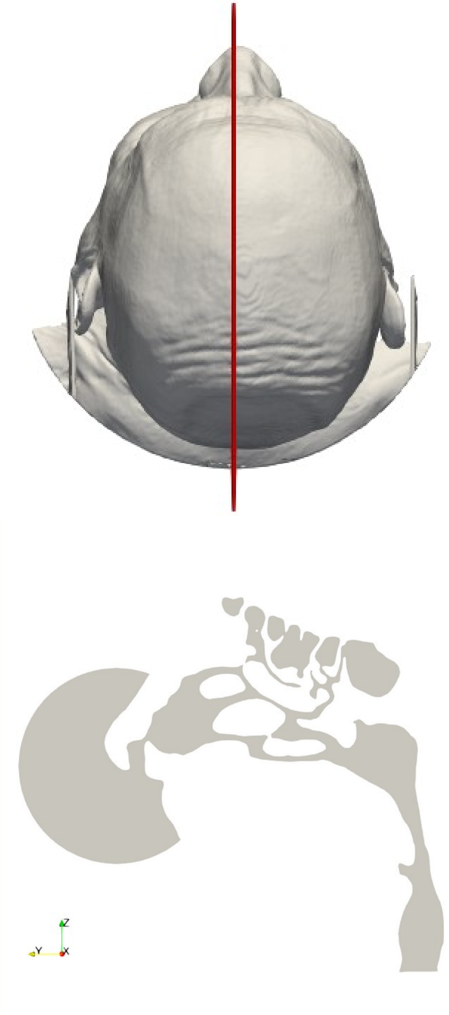
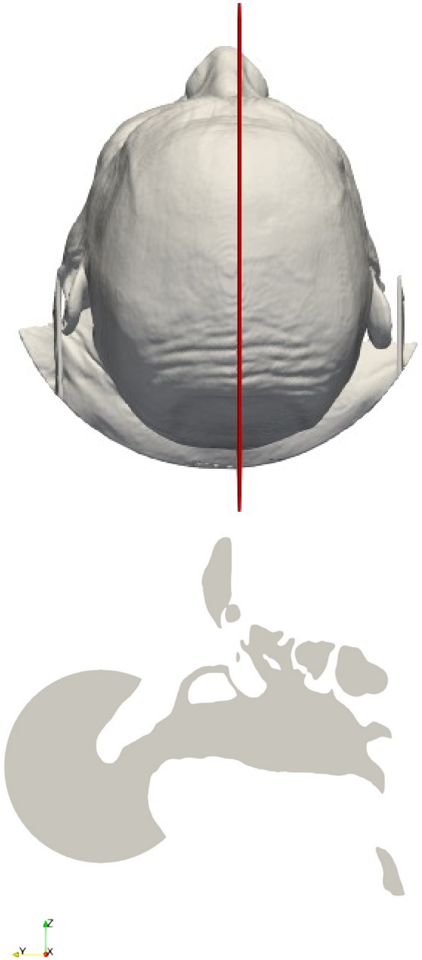
Pre-surgery (preop) results and comparison.

Slices

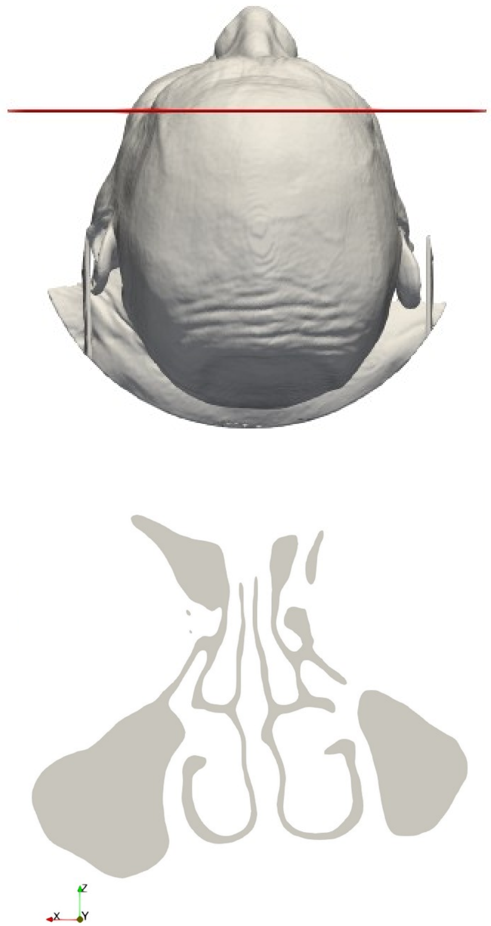
sagittal plane 1



sagittal plane 2



coronal plane



Comparisons will be carried on on the planes highlighted in red.

Pre-surgery – CPG boundary conditions

U

noseWalls

type fixedValue;

value uniform (0 0 0);

sphere

type pressureInletOutletVelocity;

value uniform (0 0 0);

throat

type pressureInletOutletVelocity;

value uniform (0 0 0);

p

noseWalls

type zeroGradient;

sphere

type totalPressure;

p0 uniform 0;

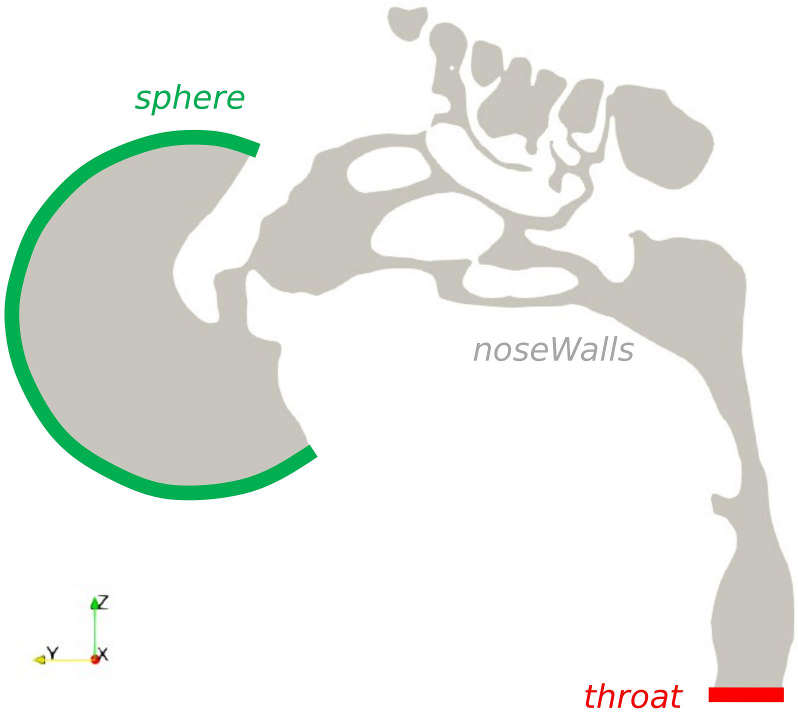
value uniform 0;

throat

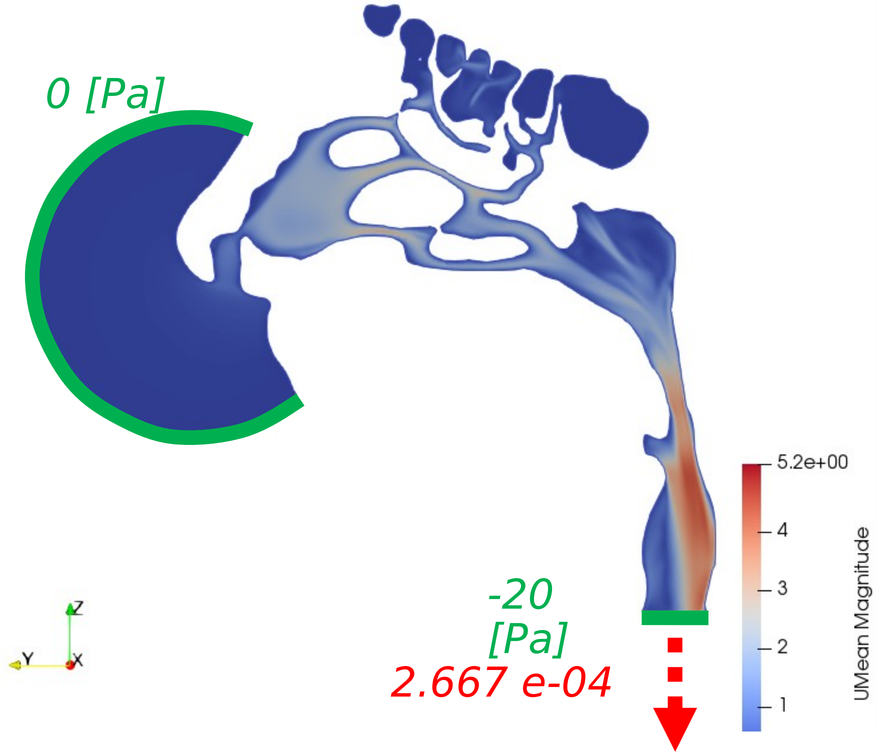
type totalPressure;

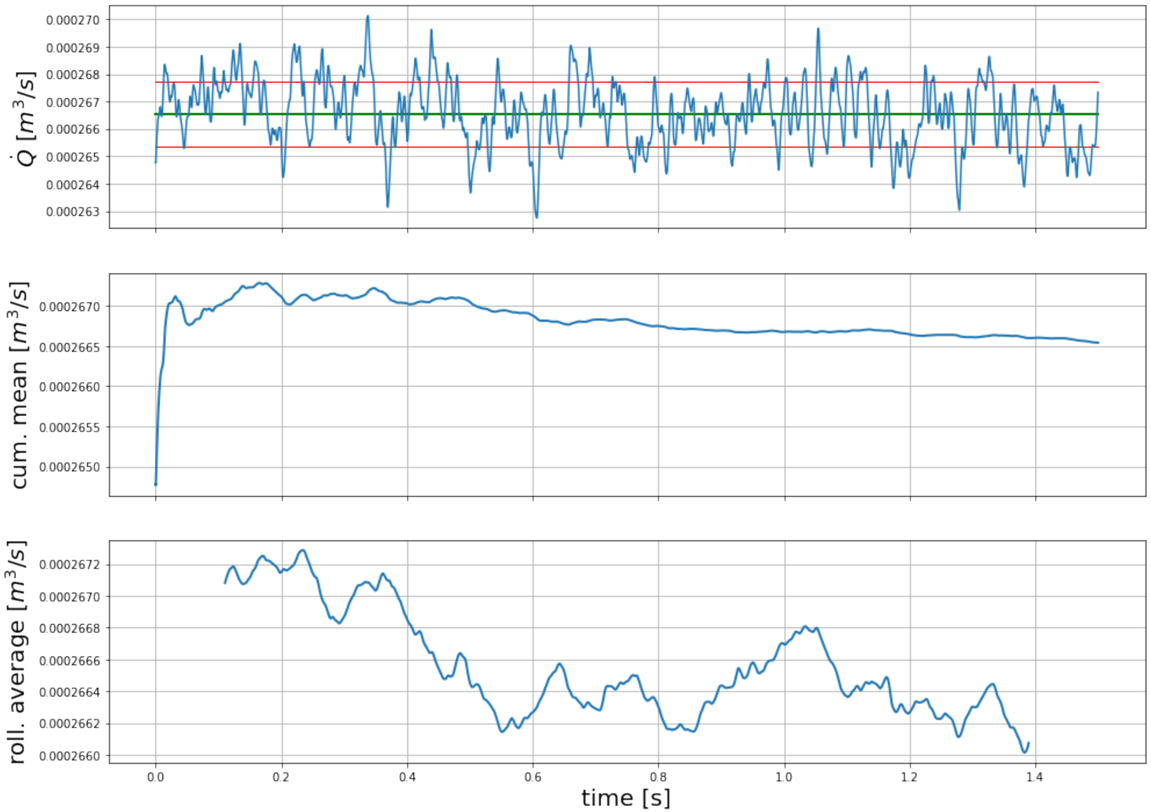
p0 uniform -20.;

value uniform 0;



Pre-surgery – CPG results & statistics





The condition of statistically steady solution is reached since the simulation is steady inside the 0.1%.

Pre-surgery – CFR boundary conditions

U

noseWalls

type fixedValue

value uniform (0 0 0)

sphere

type flowRateInletVelocity

volumetricFlowRate constant 2.667e-04

value uniform (0 0 0)

throat

type pressureInletOutletVelocity

value uniform (0 0 0)

p

noseWalls

type zeroGradient

sphere

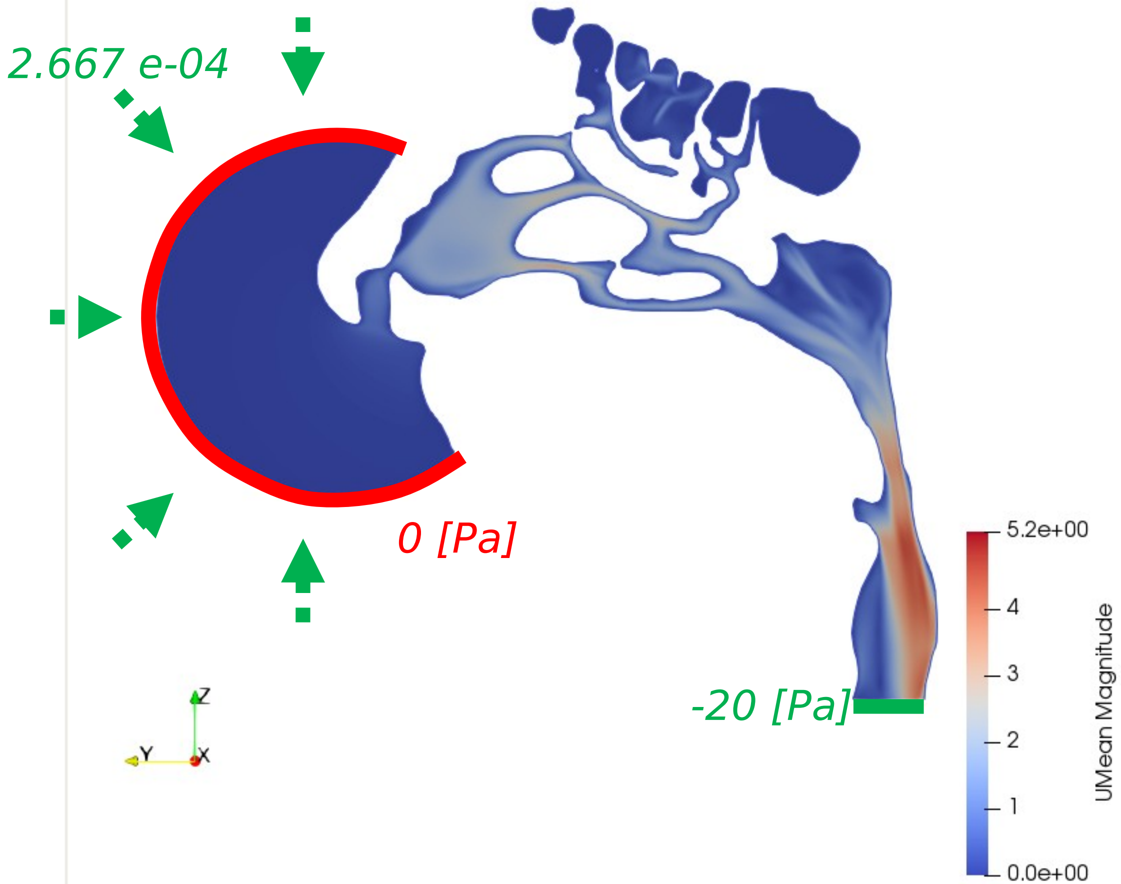
type zeroGradient

throat

type totalPressure

p0 uniform -20

value uniform 0



Pre-surgery – CPI boundary conditions

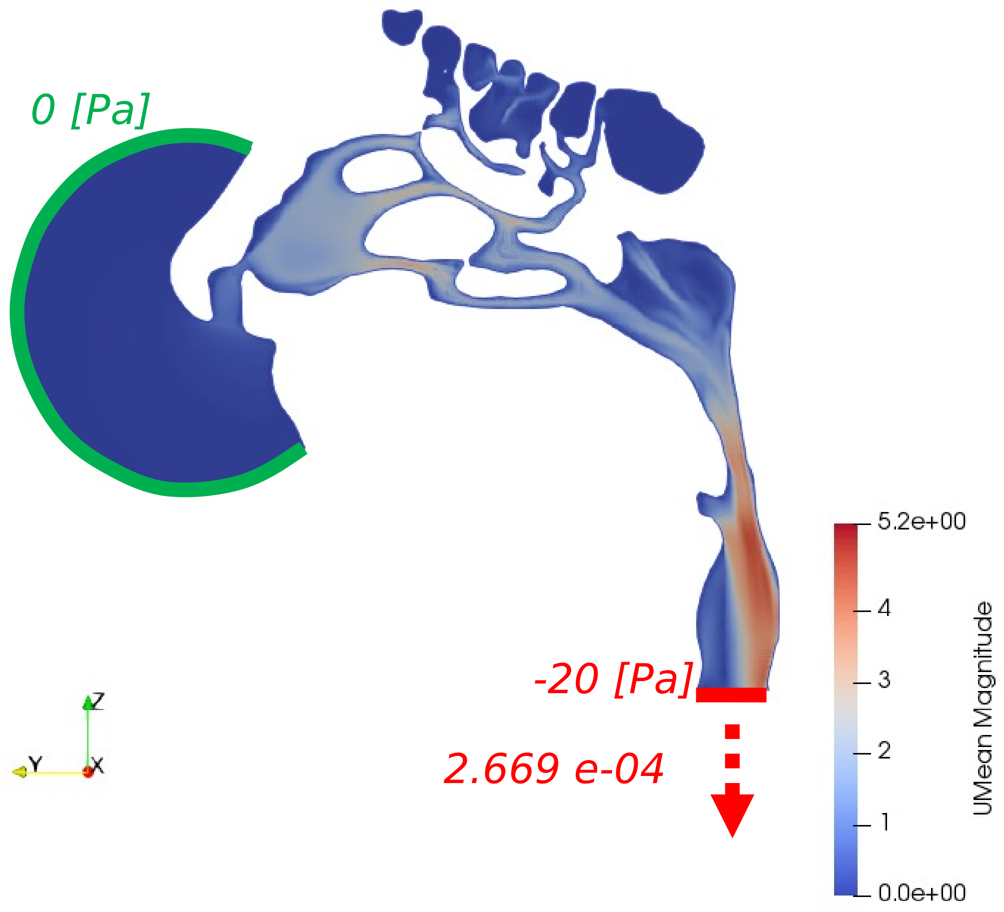
U

noseWalls
    type   fixedValue
    value   uniform (0 0 0)
sphere
    type   inletOutlet
    value   uniform (0 0 0)
throat
    type   inletOutlet
    value   uniform (0 0 0)

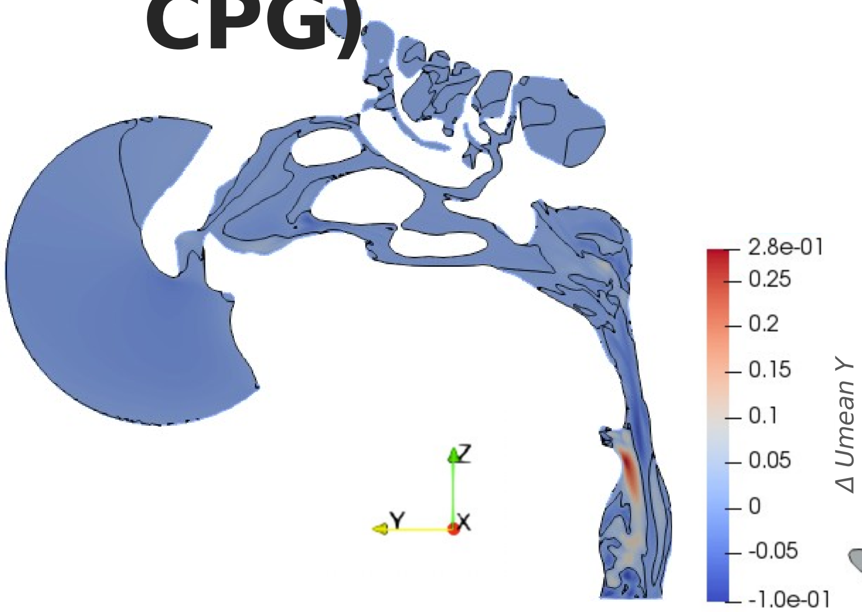
p

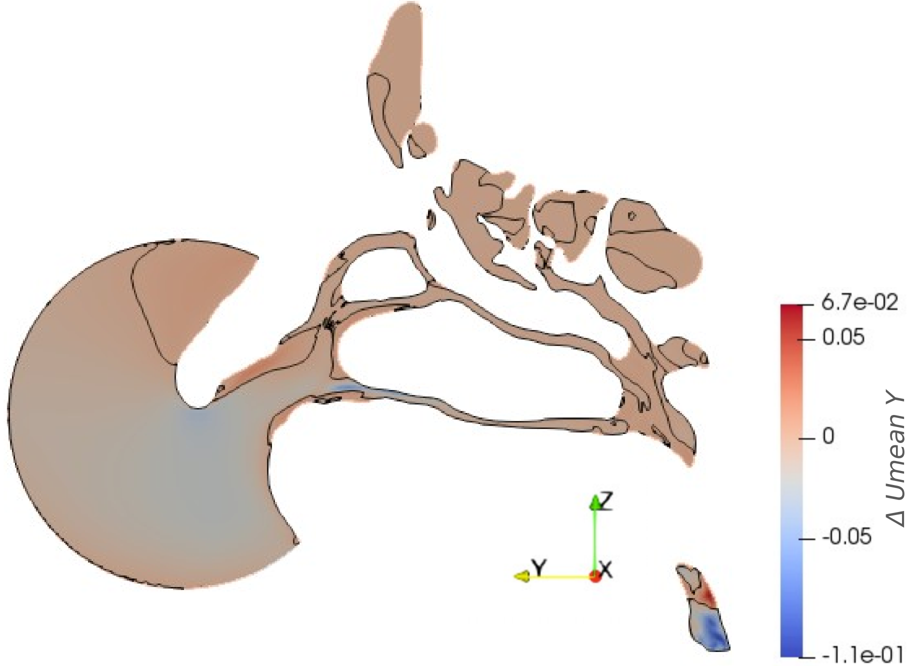
noseWalls
    type   zeroGradient
sphere
    type   totalPressure;
    p0   uniform 0;
    value   uniform 0;
throat
    type   groovyBC;
    variables   ("CPI=-0.005334;" "Qdot=sum(phi);"
);
    valueExpression "CPI/Qdot ";
    value   uniform -20;

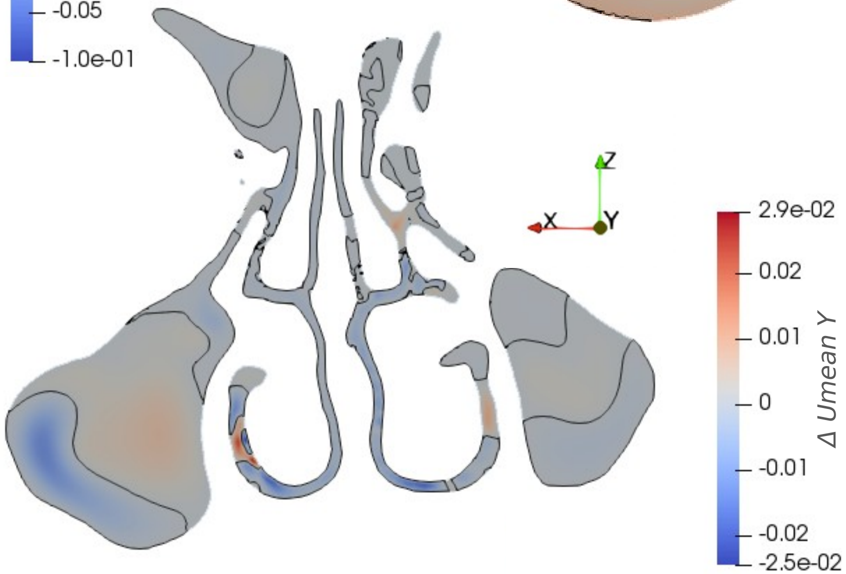
Power Input: -0.005334 ± 6.7e-09 [W]



Pre-surgery results comparison (CPI – CPG)





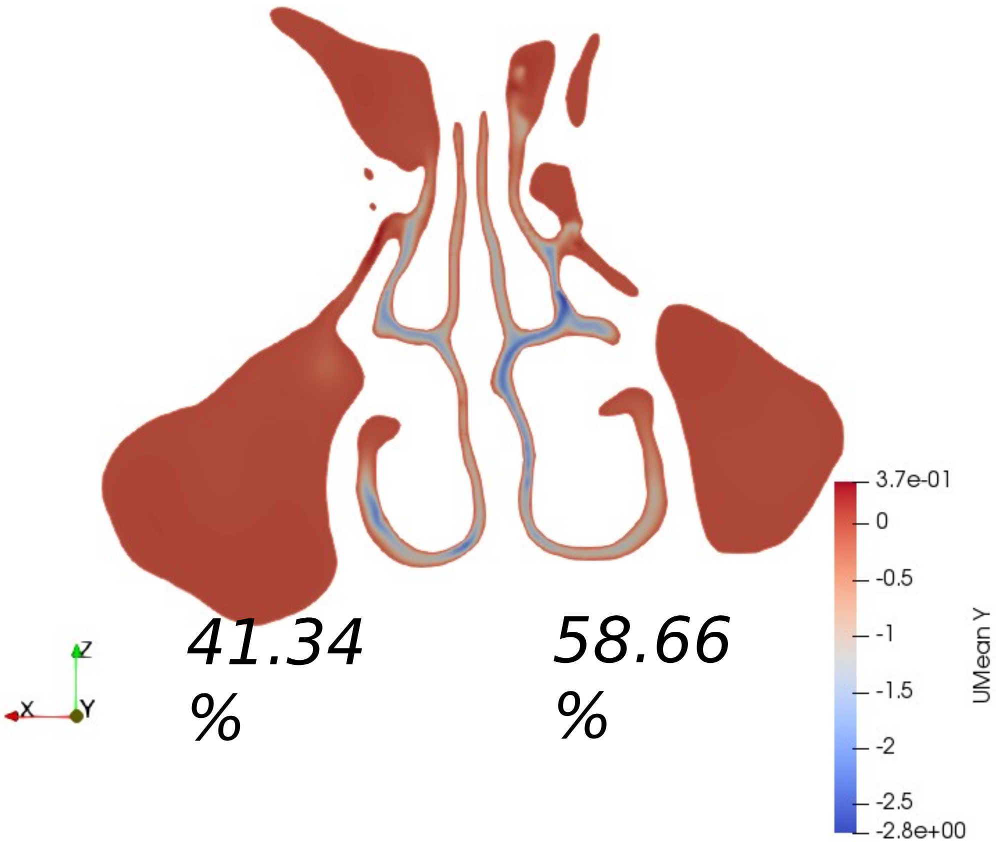


The figures show the velocity difference between CPI and CPG. In general the differences are small.

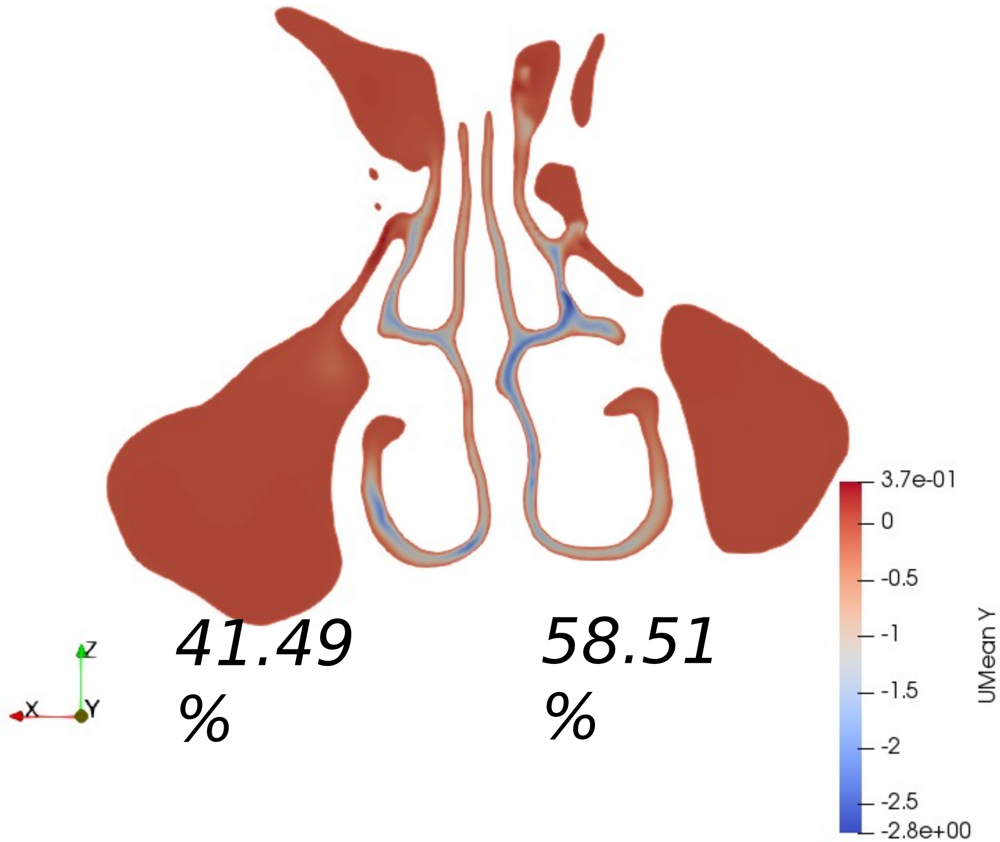
Black lines indicate zero-difference

Results – pre surgery flow distribution

preop - CPG



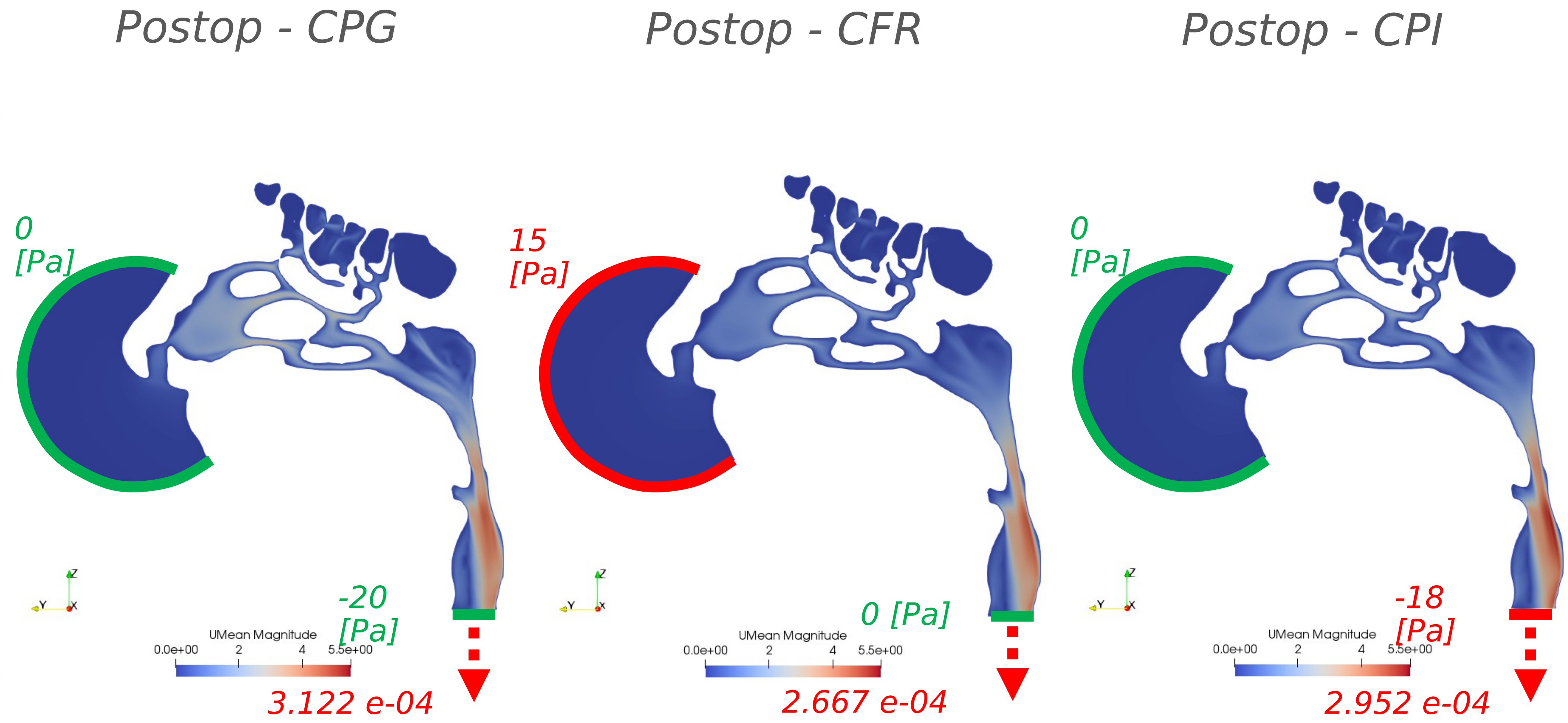
preop - CPI



The difference in the distribution of the flowrate for the preop case with CPG and CPI boundary condition is 0.145% .

Post-surgery (postop) results

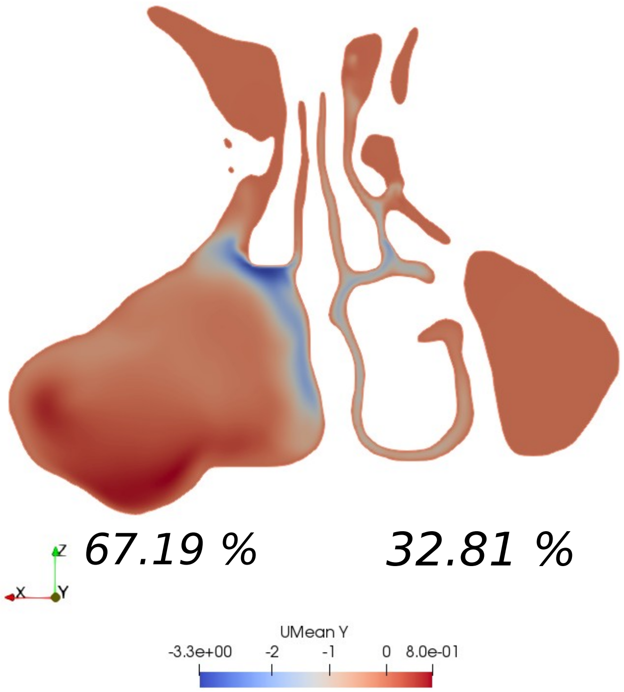
Post-surgery results



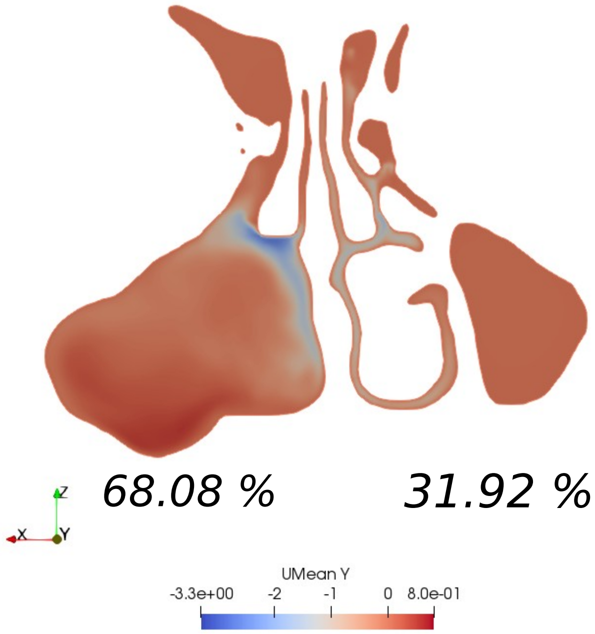
The three boundary conditions shows quite different outcomes.

Post-surgery results

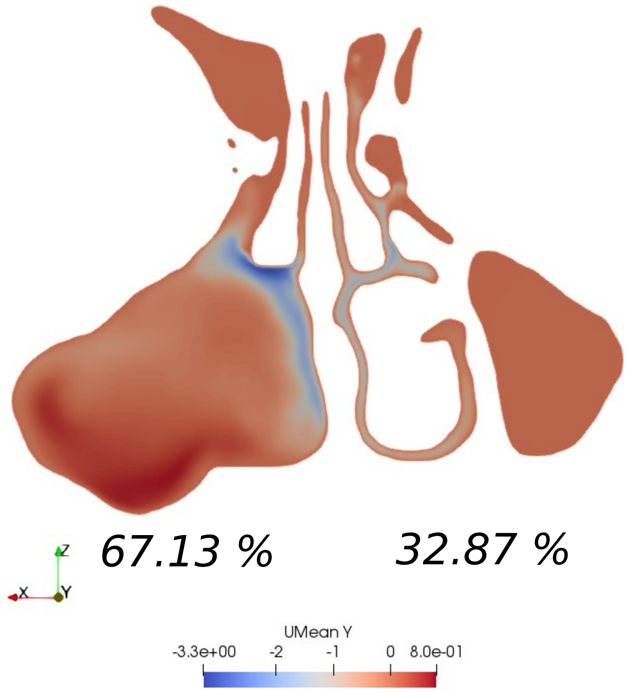
Postop - CPG



Postop - CFR



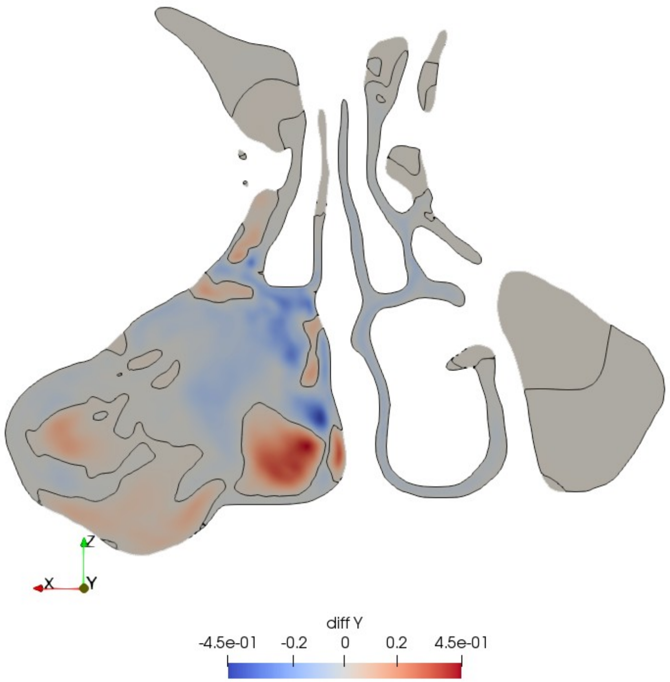
Postop - CPI



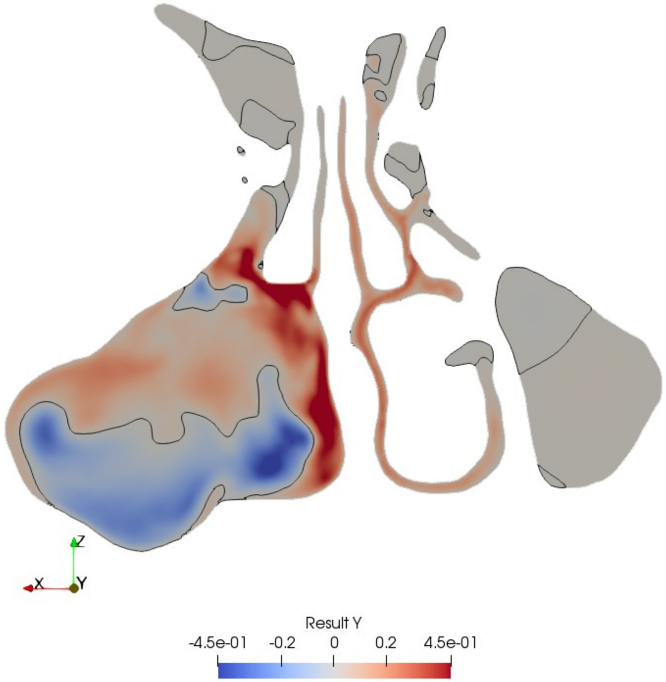
Flowrate distribution among the nostrils shows almost the same imbalance in all the solutions.

Post-surgery results comparison

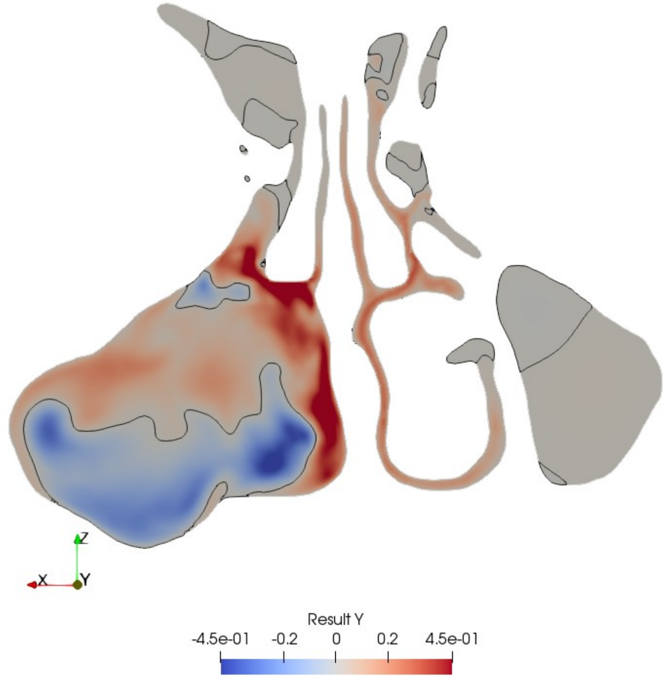
CPI - CPG



CPG - CFR



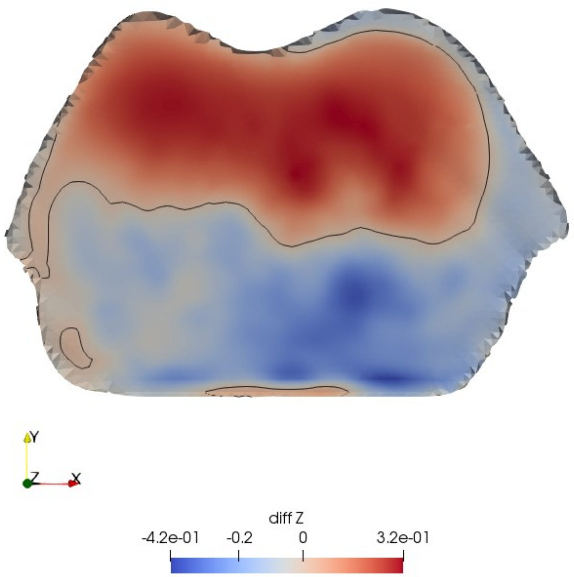
CPI - CFR



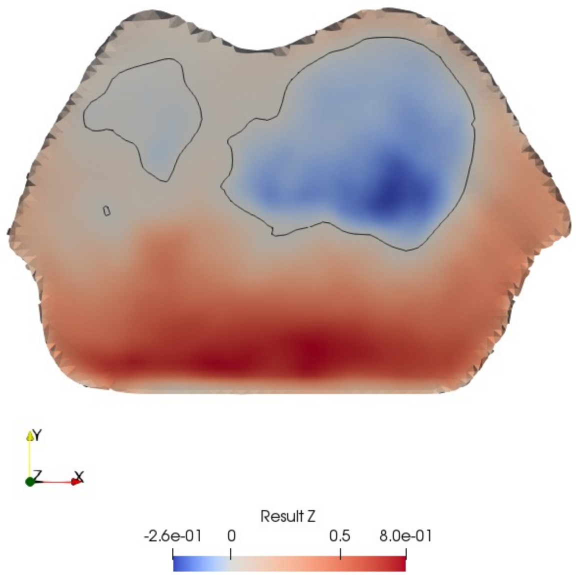
Y-UMean differences are larger than in the preop case.

Post-surgery results comparison

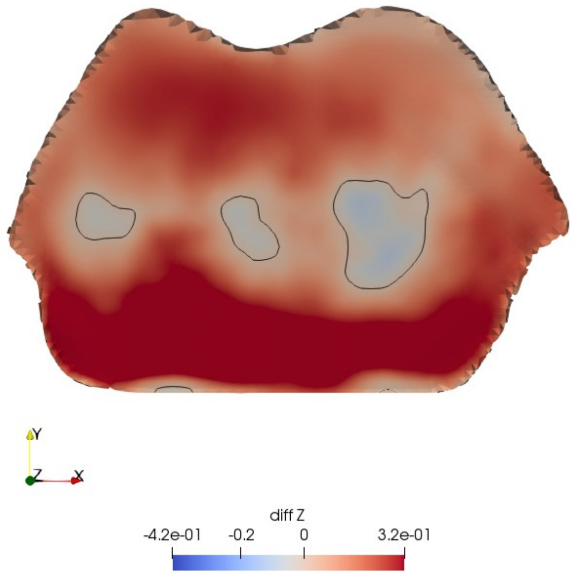
CPI - CPG



CPG - CFR



CPI - CFR



CPI and CPG boundary conditions show different behaviour at the outlet patch: in the CPI the outflow is more concentrated on the back of the Trachea.

It can be noted the mesh degradation close to the patches.

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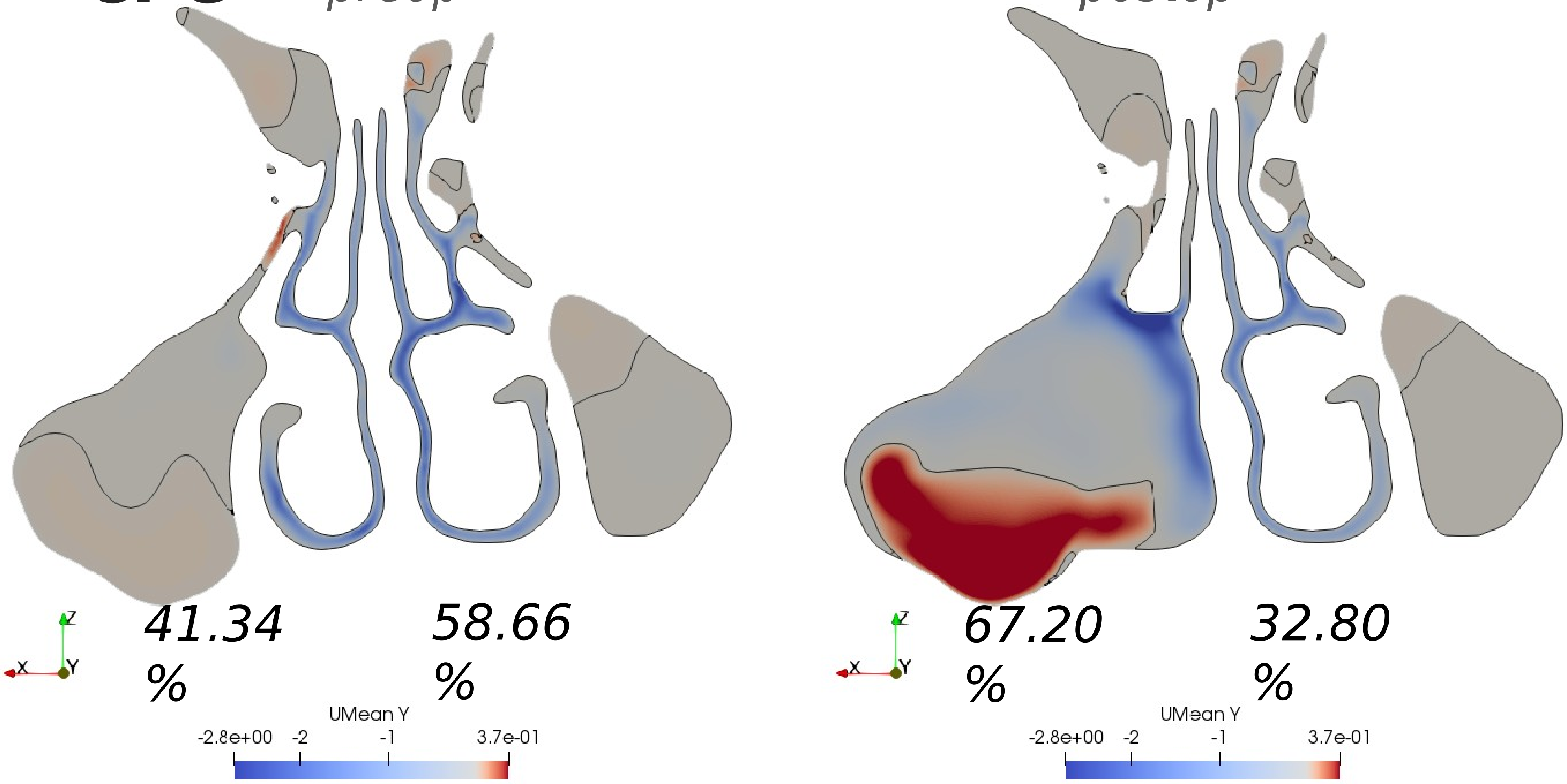
Comparison of preop and postop

Results – the effects of surgery with CPG

preop *postop*

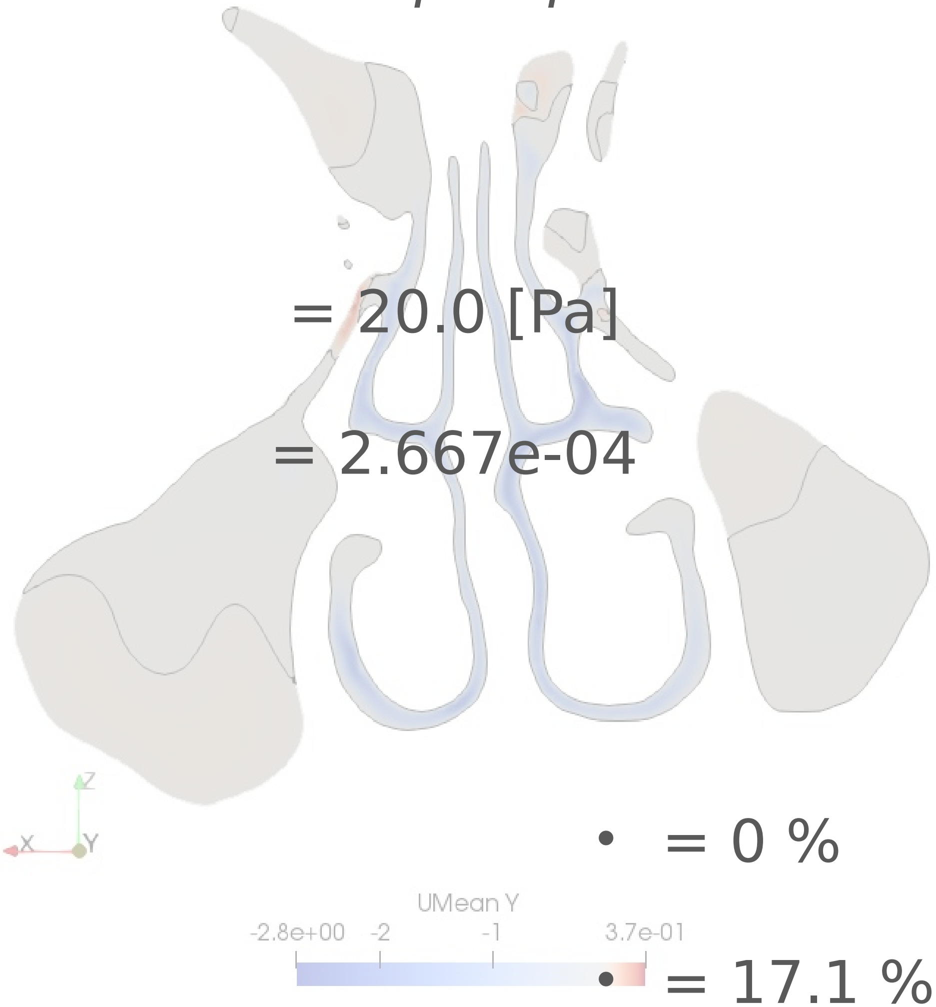


The slices are coloured with the UMean along Y axis. Black line is the zero velocity line.

Flowrate distribution among the nostrils. Huge imbalance after the surgery.

Results – the effects of surgery with CPG

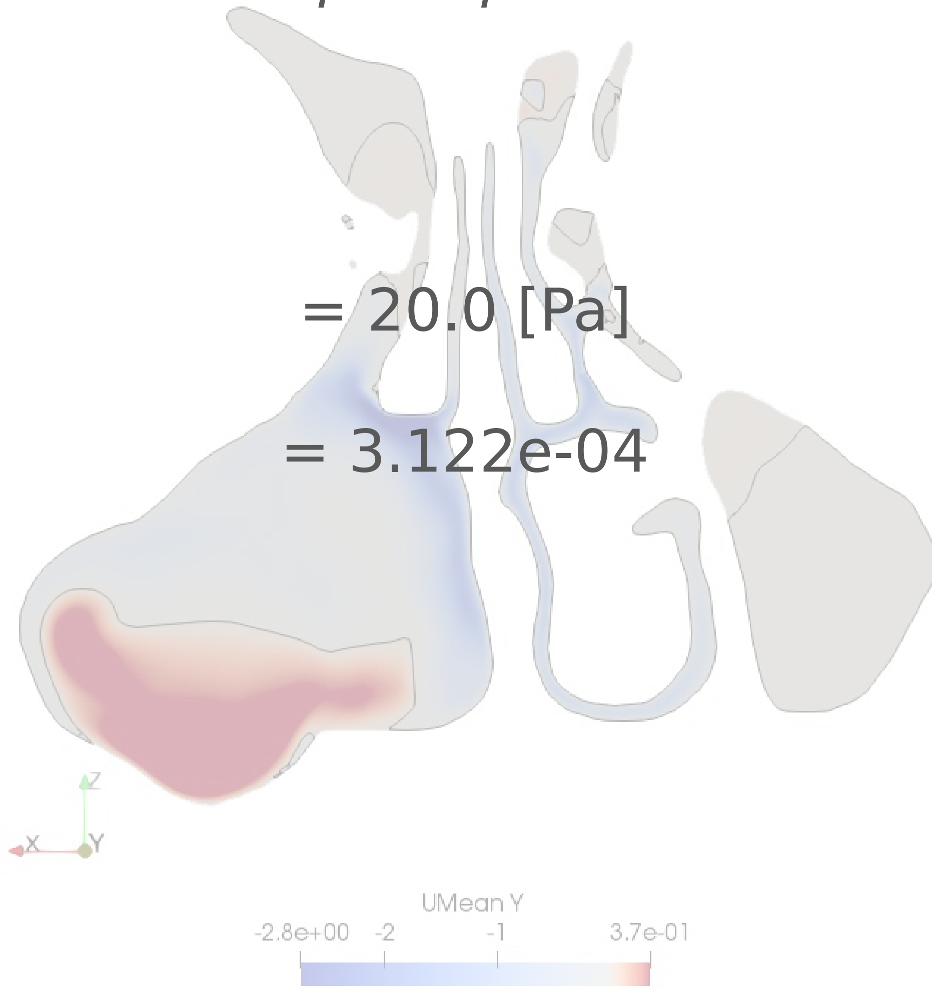
preop



= 20.0 [Pa]

= 2.667e-04

postop



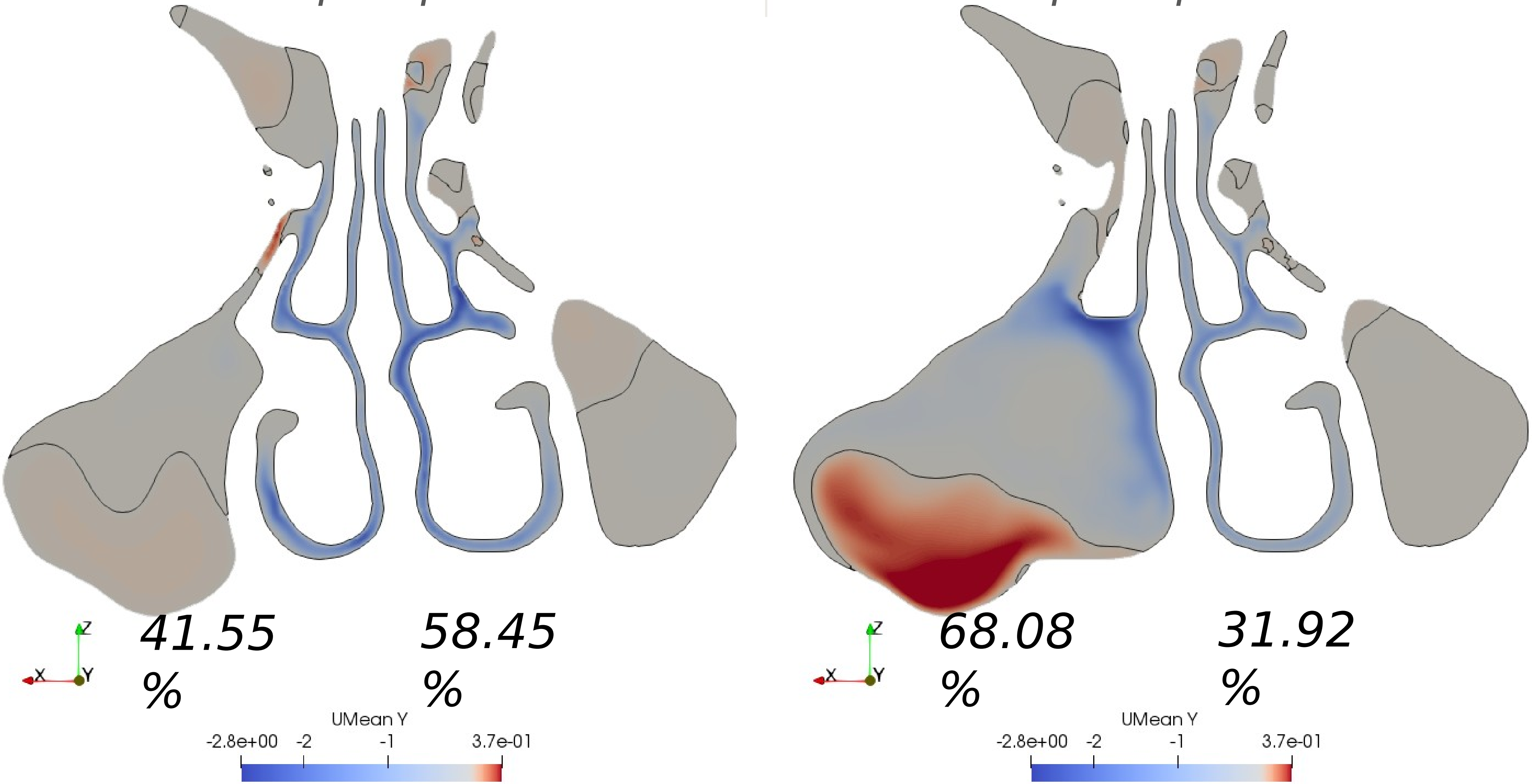
= 20.0 [Pa]

= 3.122e-04

- = 0 %
- = 17.1 %

Results – the effects of surgery with CFR

preop *postop*

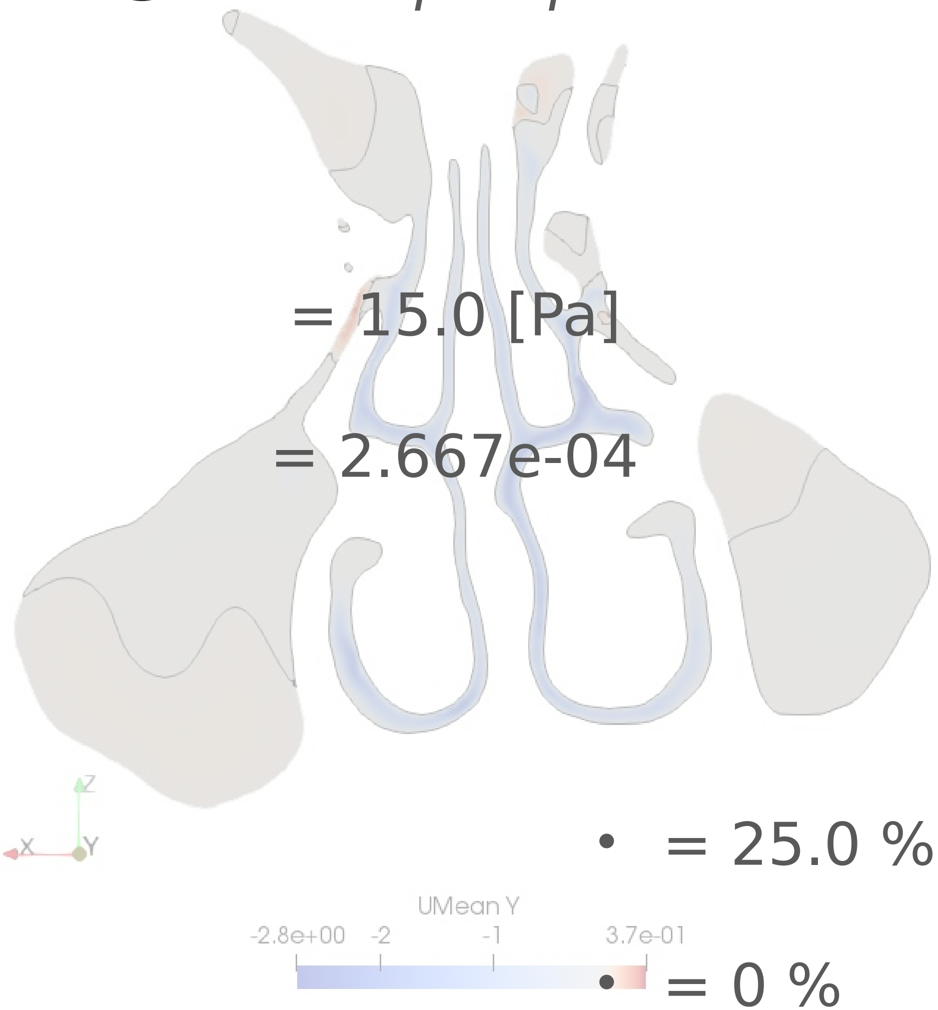


The slices are coloured with the UMean along Y axis. Black line is the zero velocity line.

Flowrate distribution among the nostrils. Huge imbalance after the surgery.

Results – the effects of surgery with CFR

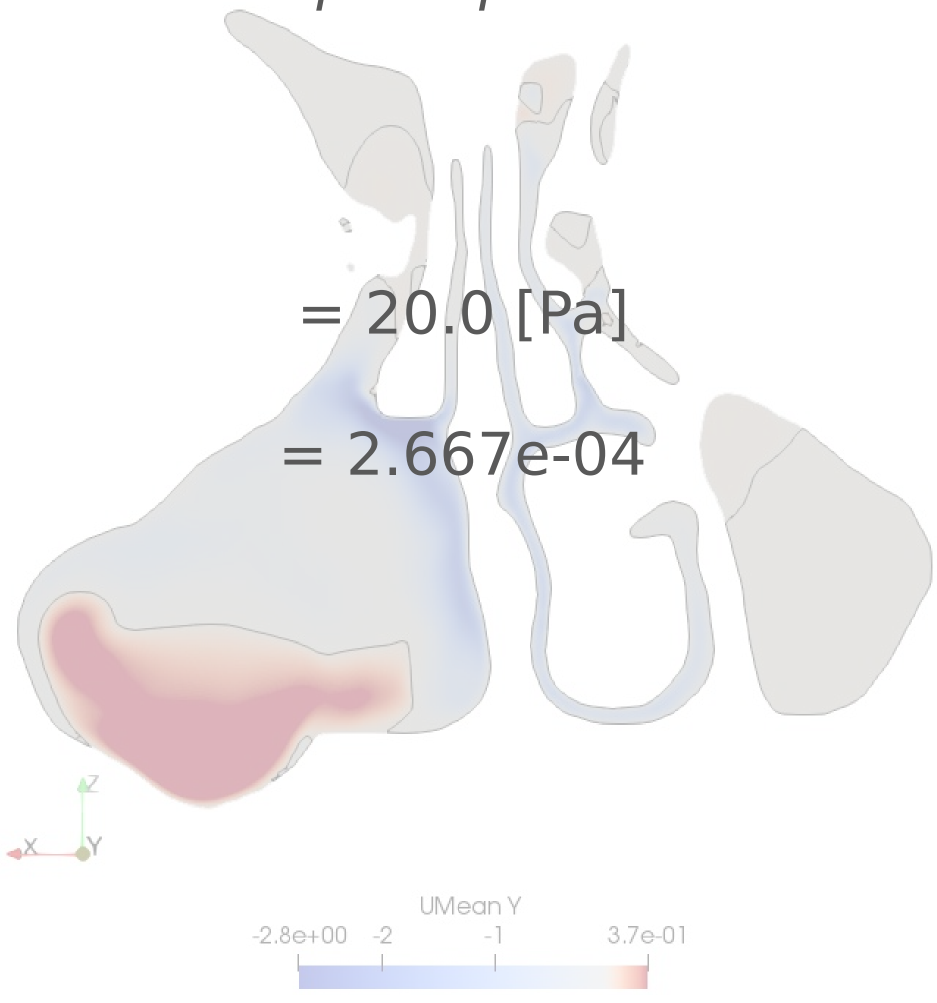
preop



= 15.0 [Pa]

= 2.667e-04

postop

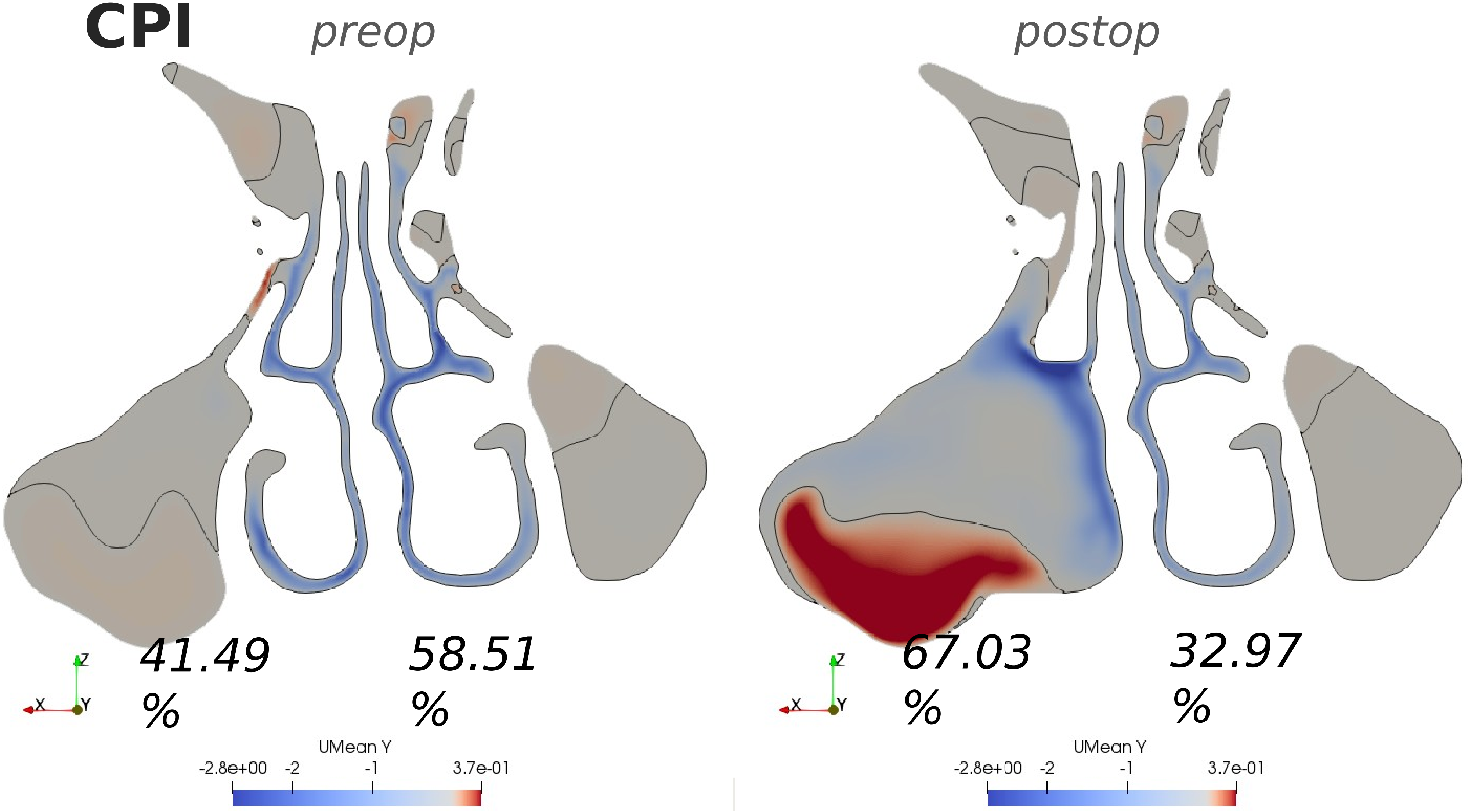


= 20.0 [Pa]

= 2.667e-04

- = 25.0 %
- = 0 %

Results – the effects of surgery with CPI

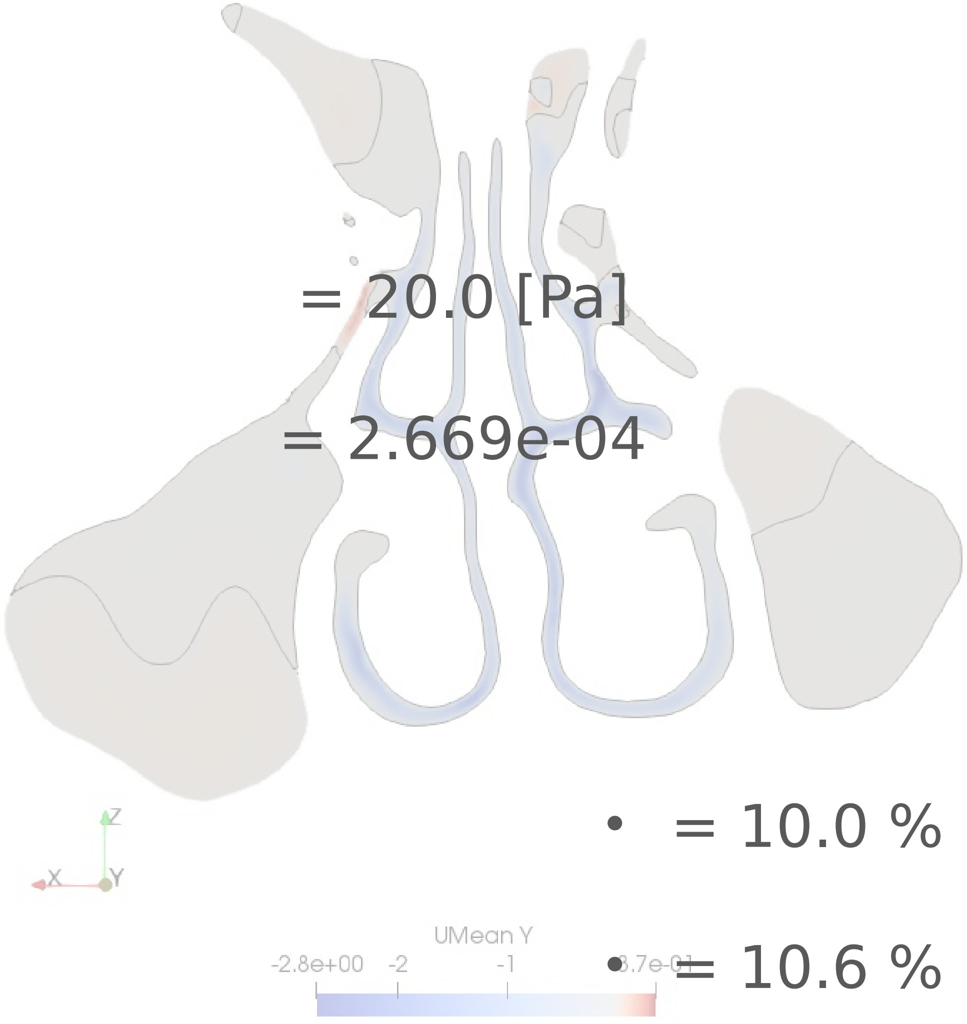


The slices are coloured with the UMean along Y axis. Black line is the zero velocity line.

Flowrate distribution among the nostrils. Huge imbalance after the surgery.

Results – the effects of surgery with CPI

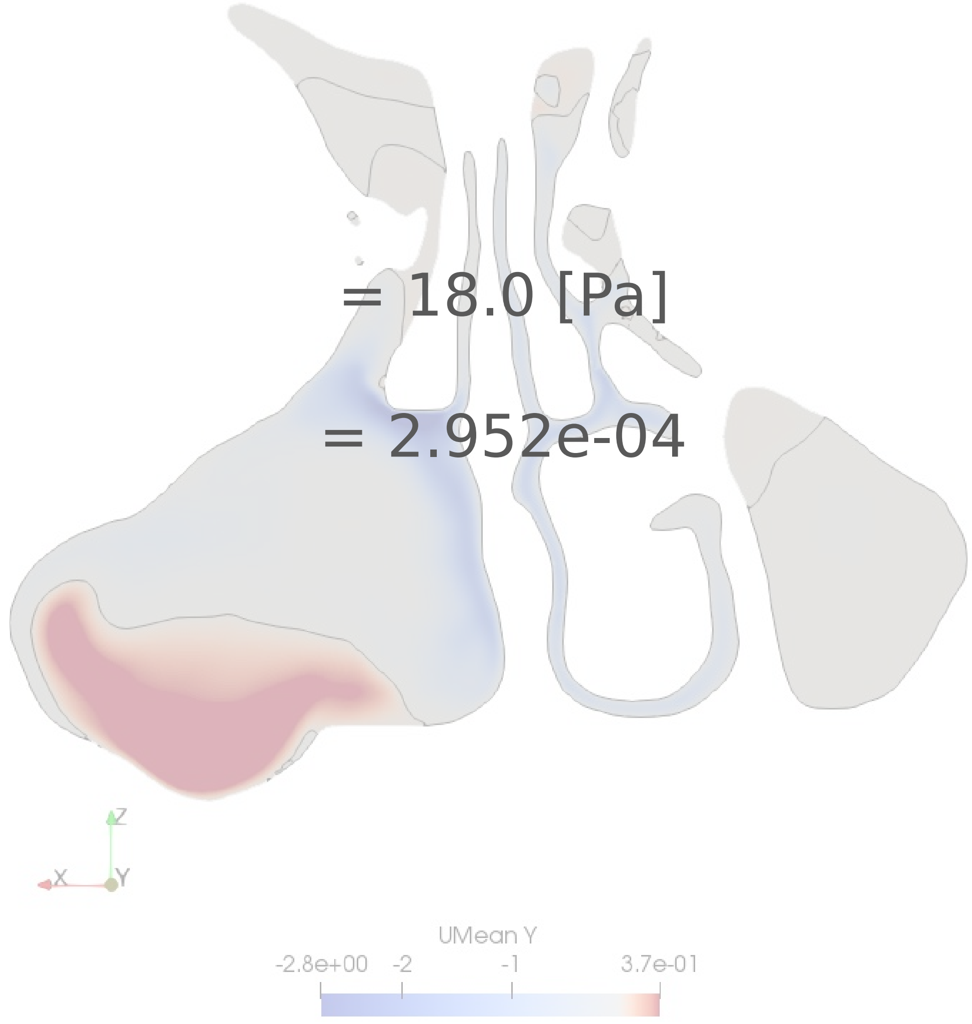
preop



= 20.0 [Pa]

= 2.669e-04

postop



= 18.0 [Pa]

= 2.952e-04

- = 10.0 %
- = 10.6 %

Results summary

	CPG preop	CPG postop	CFR preop	CFR postop	CPI preop	CPI postop
	2.665e-4	3.122e-04	2.667e-4	2.667e-04	2.669e-04	2.952e-04
ΔP [Pa]	20.015	20.024	20.003	15.020	19.998	18.070
CPI [W]	5.738e-03	6.252e-3	5.339e-3	4.010e-3	5.334e-03	5.334e-03
Δ [%]	17.1 %		25.0 %		10.6 % 10.0%	

Conclusions

- For the first time, a quantitative and qualitative comparison between CPG, CFR, CPI has been made.

Boundary condition	CPG		CFR		CPI	
cases	Pre-op	Post-op	Pre-op	Post-op	Pre-op	Post-op
	2.665e-04	3.122e-04	2.667e-04	2.667e-04	2.669e-04	2.952e-04
ΔP [Pa]	20.015	20.024	20.003	15.020	19.998	18.070
CPI [W]	5.738e-03	6.252e-3	5.339e-03	4.010e-03	5.334e-03	5.334e-03
[%]	17.1 %		25.0 %		10.6 % 10.0%	

- Clearly, the differences are large
- No clinician today is able to say which condition is the correct one to use
- CPG is clearly the worst condition since it depends strongly on the shape (for instance trachea length)
- The use of CFR or CPI (or something else) is a future discussion to make with clinicians