Fluid Dynamics of the Human Nose:
An overview of clinical perspectives enabled by CFD

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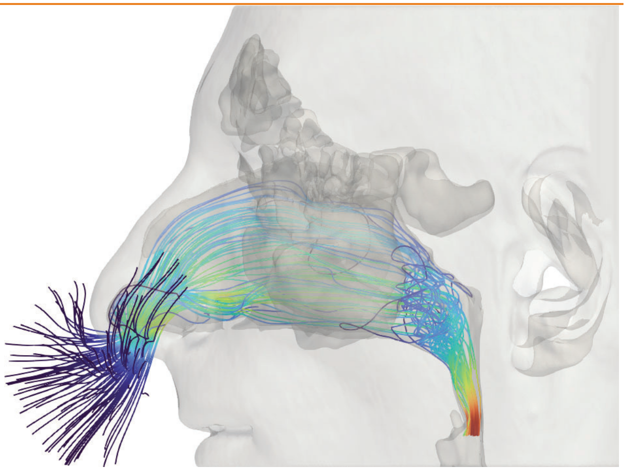
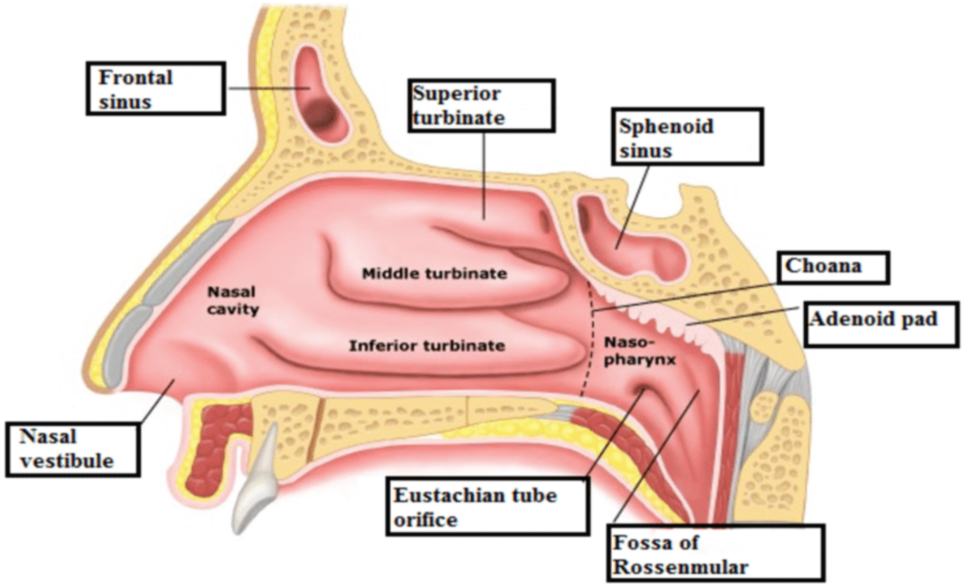
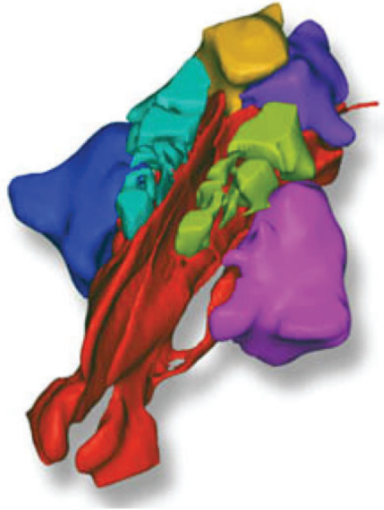
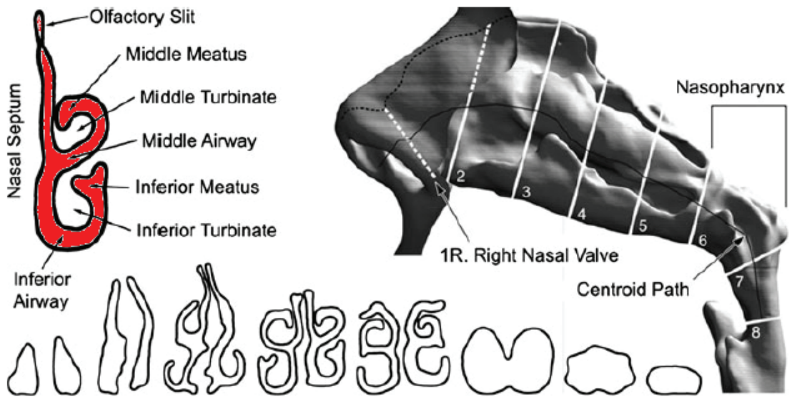
EFMC14, Athens, Sept 14, 2022



The human nose: functions and anatomy







Is the nose flow important?

- At least 1/3 of the adult world population is troubled with nasal breathing difficulties[1]
- In 2014, the one-year (only!) cost of cronic rhinosinusits (alone!) in US (only!) was $22bn[2]
- Certain nose surgeries have 50% failure rate[3]

Huge room for improvement!

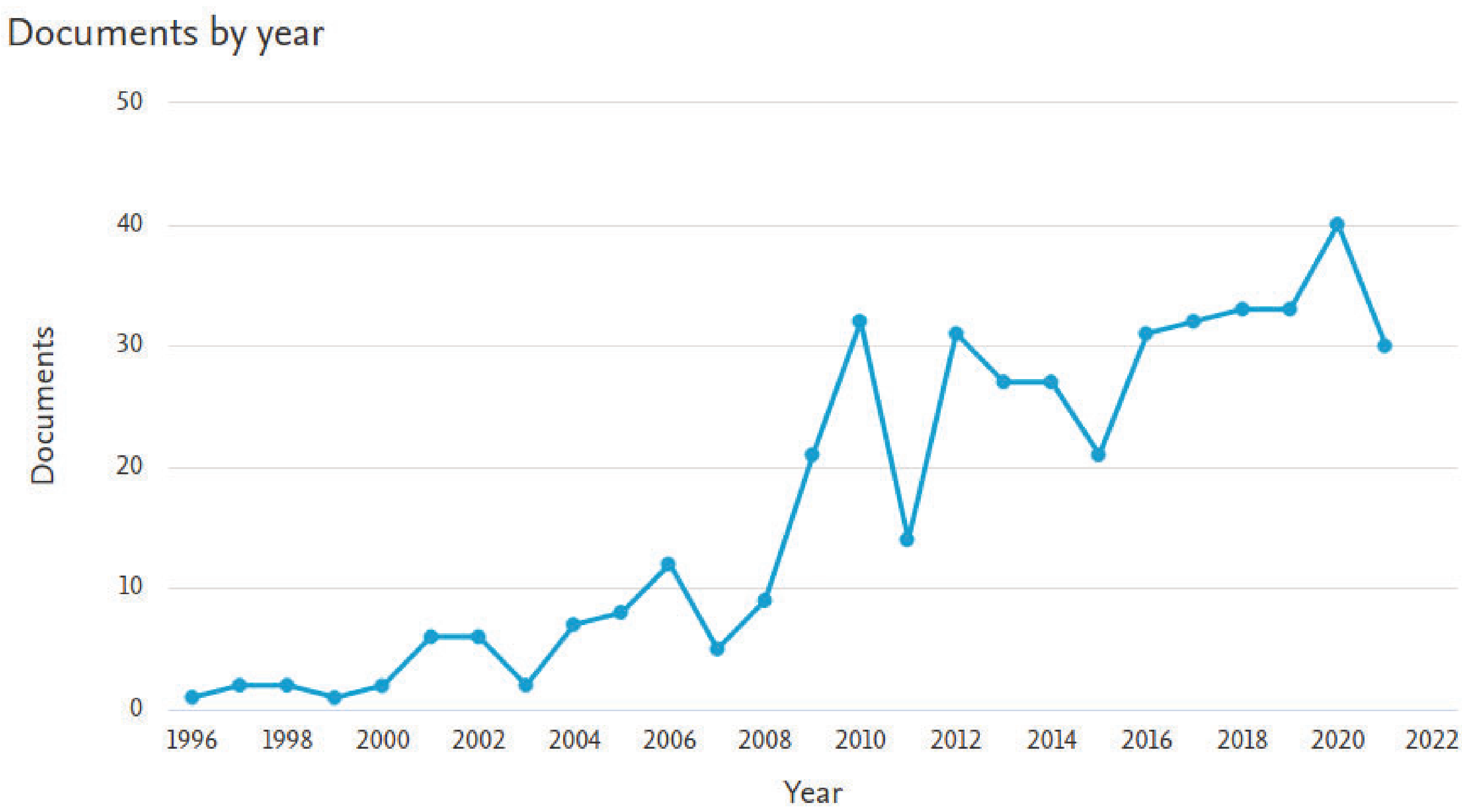
[1] Stewart *et al.* Int J Gen Med 2010

[2] Smith *et al.* The Laryngoscope 2015

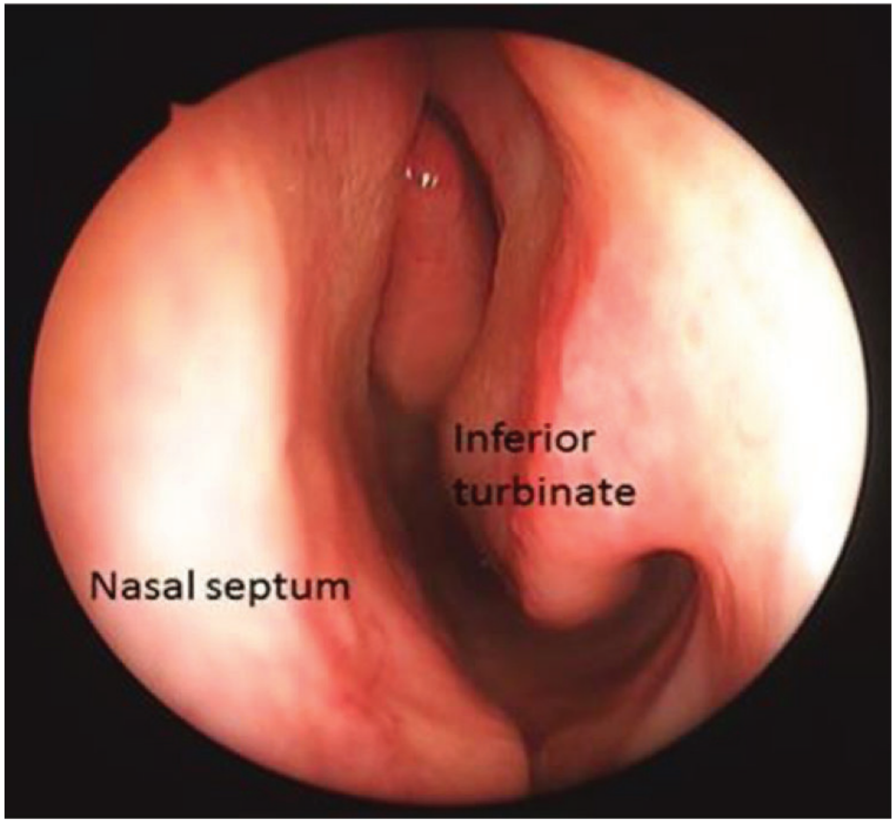
[3] Sundh & Sonnergreen, Eur Arch Otholaringol 2015

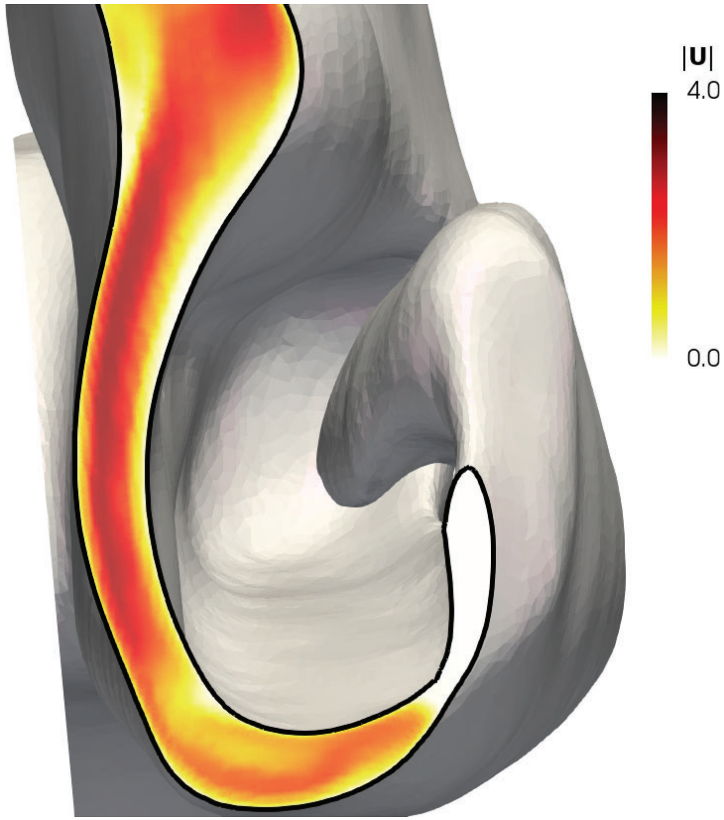
The contribution of fluid mechanics

Scopus query: ”CFD” + ”nasal”



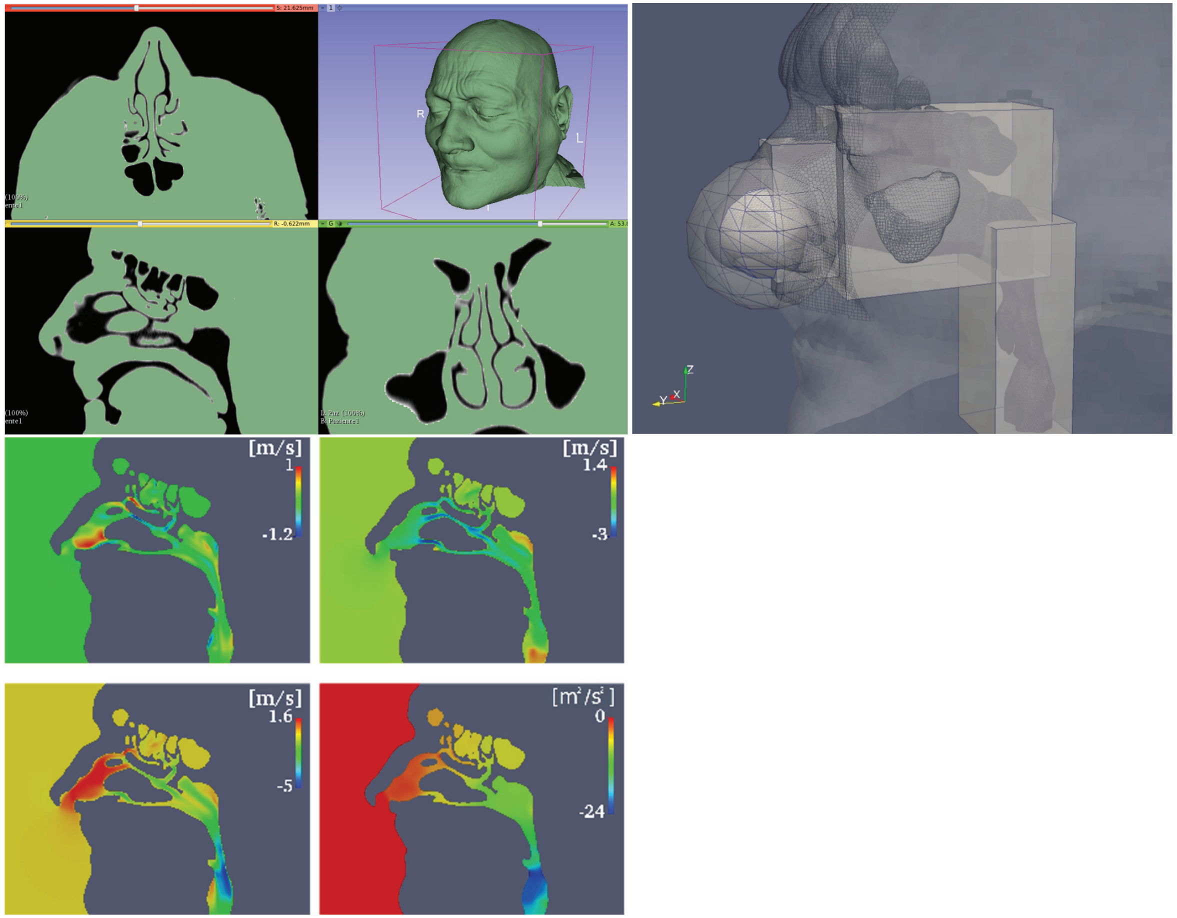
Form *and* function





The workflow: from CT scan to...

1. Segment the CT scan
2. Build a volume mesh
3. Compute a CFD solution (DNS, LES, RANS, ...)



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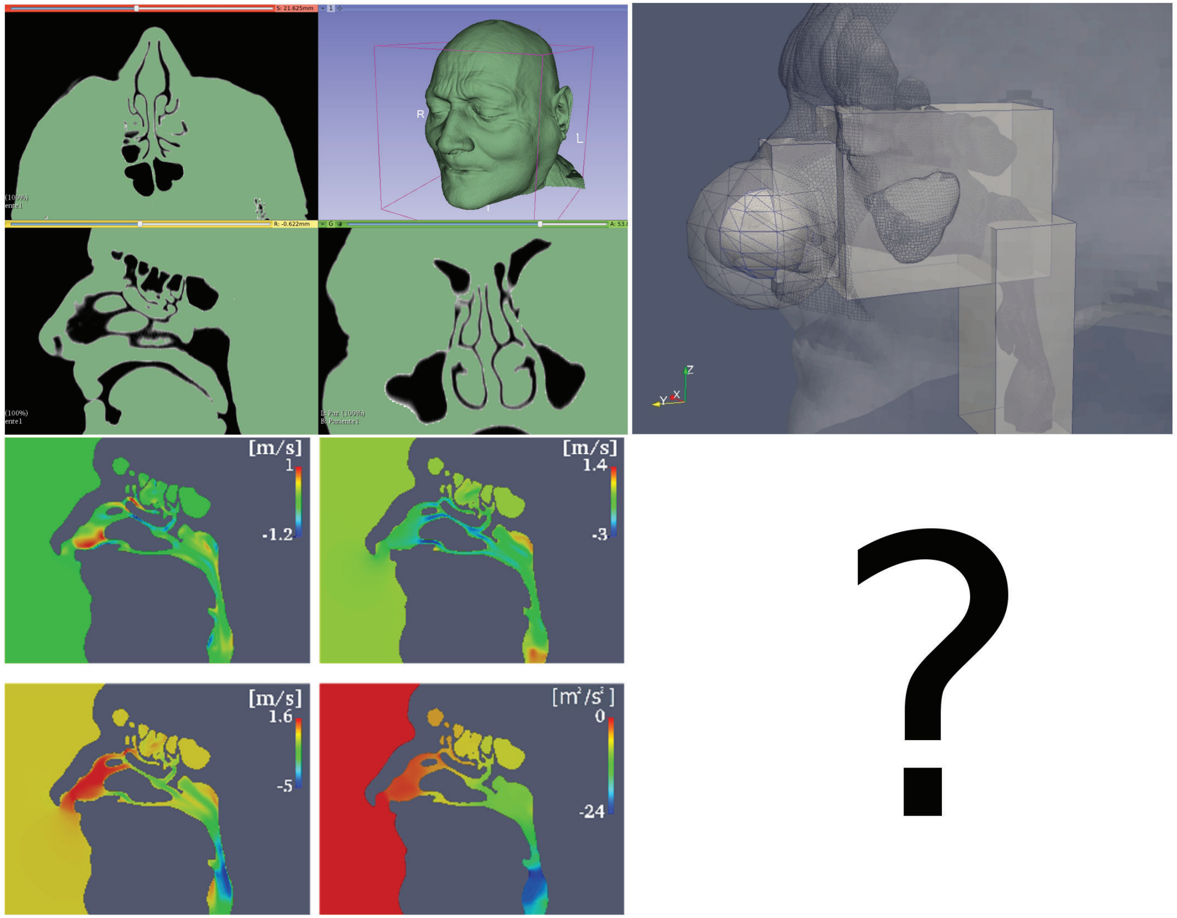
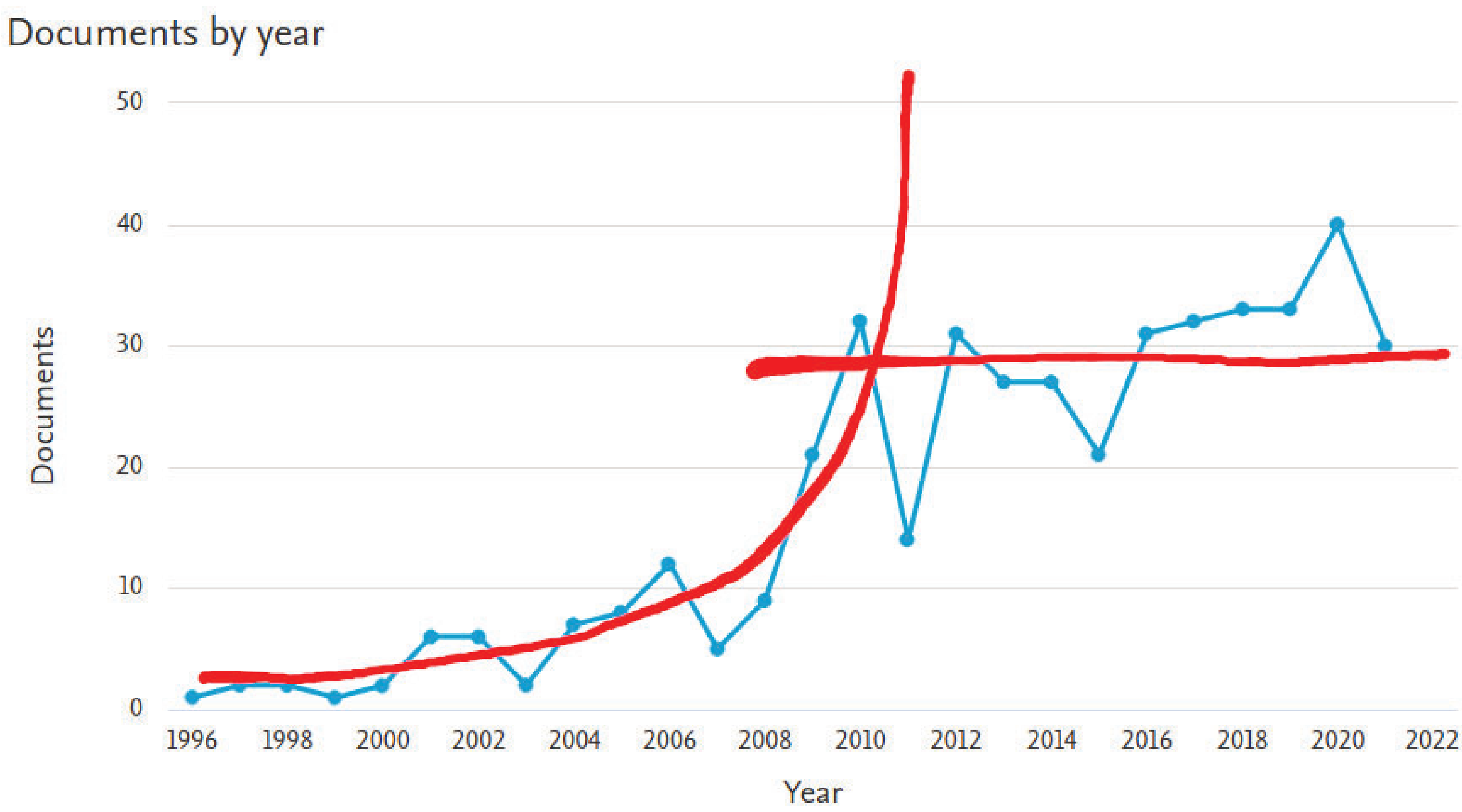


?

Only academic?

Scopus query: ”CFD” + ”nasal”



How to proceed?

Bringing CFD into the clinical setting requires:

1. Assess reliability through a solid benchmark
2. Extract CFD-derived information that is useful to surgeons

The benchmark

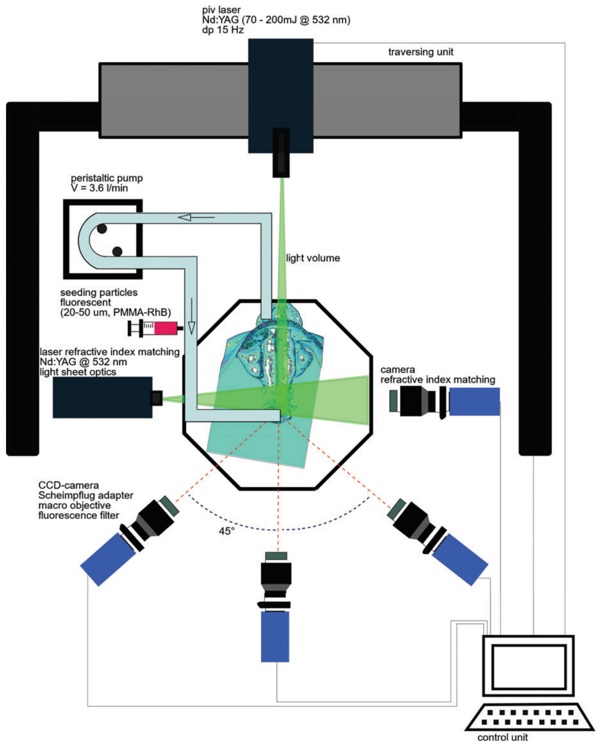
Reliability

- An unique Reynolds number does not exist
- Most authors use RANS, but the flow is not turbulent
- Most authors use steady RANS, but the flow is low-*Re* and unsteady
- Accuracy of discretization is critical

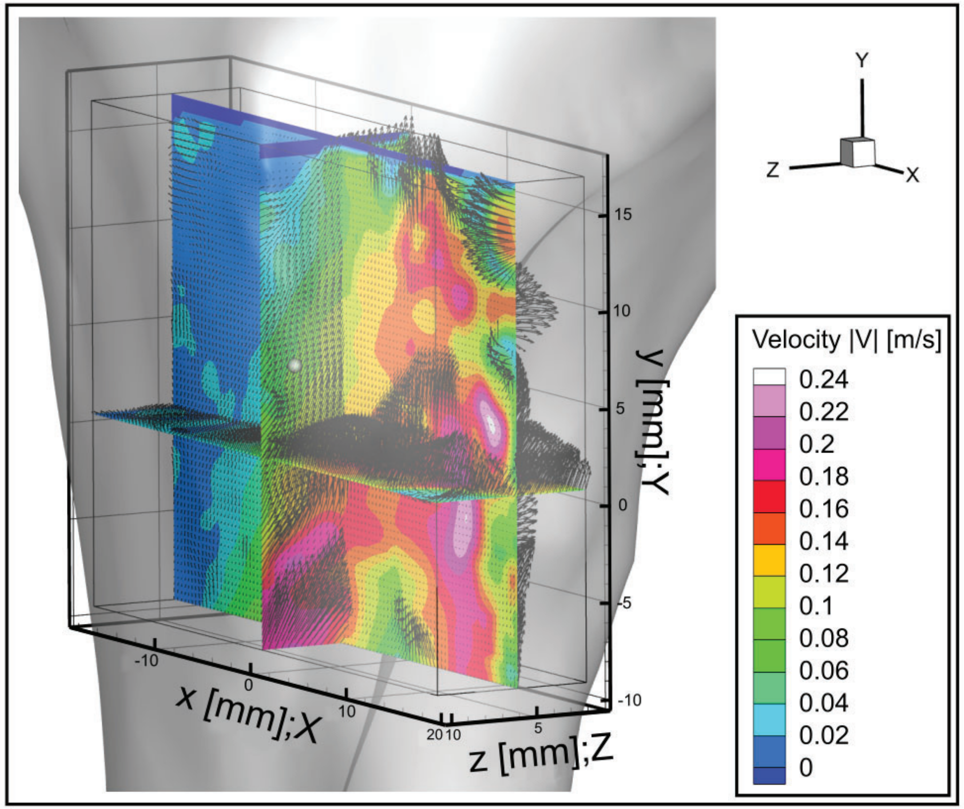
The major limiting factor is lack of reproducibility: anatomies are sensible information!

Creating a benchmark: a tomo-PIV experiment

- Based at OTH Regensburg (D)
- Patient-specific phantom model from CT scan
- Tomo-PIV at 15Hz, reconstruction volume $\approx 1000^3$ voxels



An instantaneous snapshot of the flow



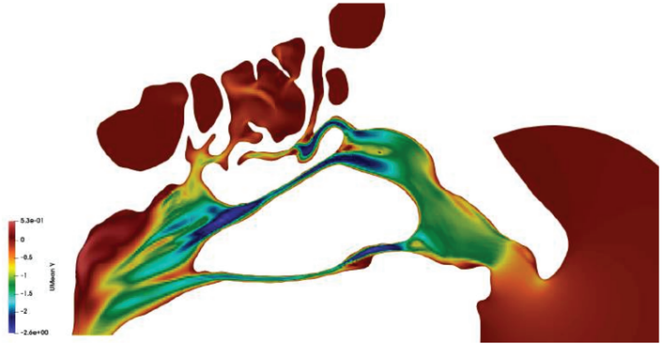
Is CFD clinically viable?

Currently, classic CFD (90% RANS, 9% LES) is too expensive for surgery planning:

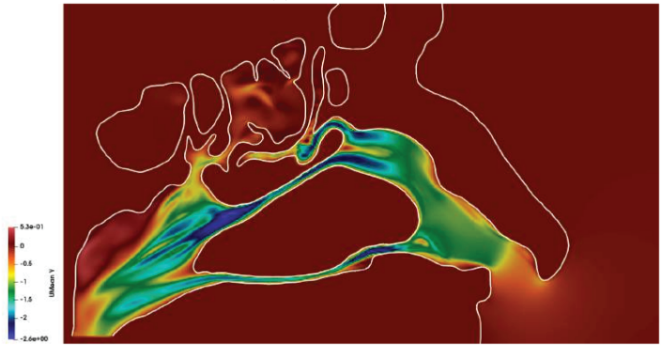
- Money
- Time
- Skills

An *ad-hoc* DNS solver

- Immersed-boundary, takes STL as input
- Verified II-order convergence
- 10-100x faster than OpenFOAM
- Speed compatible with a clinical setting
- (General interest?)



(a) OpenFOAM



(b) STLIMB

How to extract useful information

The lack of the *functionally normal* nose

CFD solution alone does not help surgeons to find the best surgery

- Main reason: lack of functionally normal reference nose
- Shape optimization problem, but an objective function is lacking
- Strong inter-subject anatomical variations with different functional significance

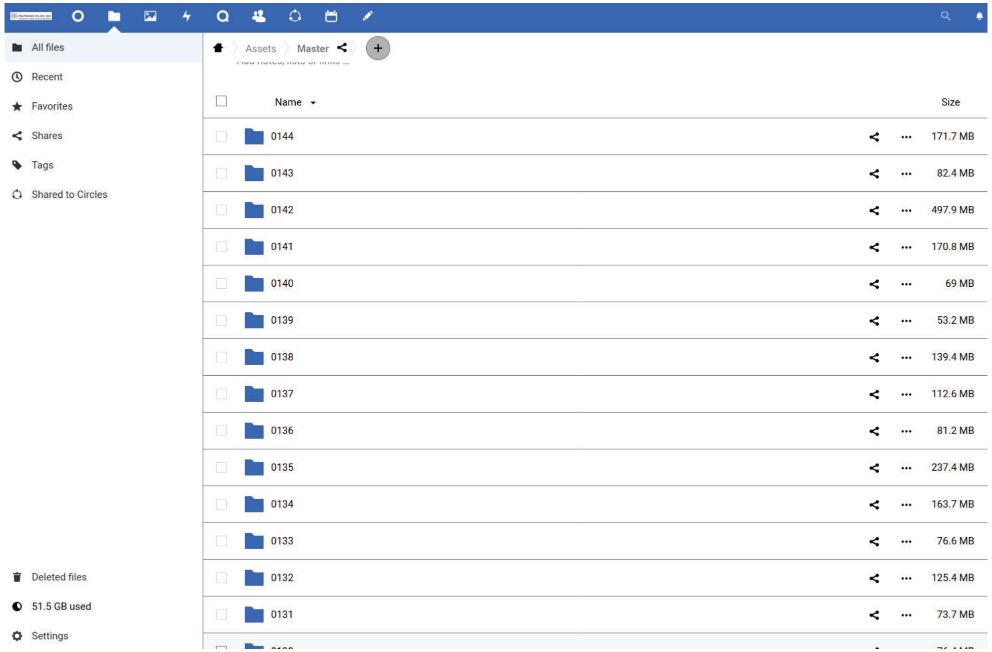
We pursue two approaches, without and with an objective function

Big Data

Database of:

- CT scans
- rhinomanometry data
- ENT evaluation sheet

Open and labeled data: huge value!



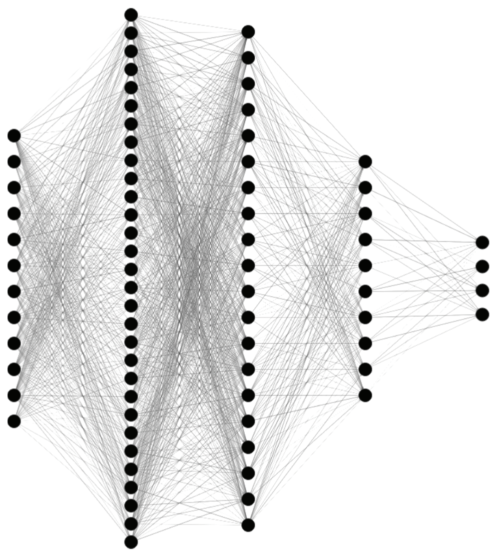
Machine Learning, our way

- Our approach: augment ML with CFD information
- Hypothesis: the flow field amplifies anatomic information
- Convection is exploited to ”bring out” information (e.g. along streamlines)

A neural network to predict pathologies

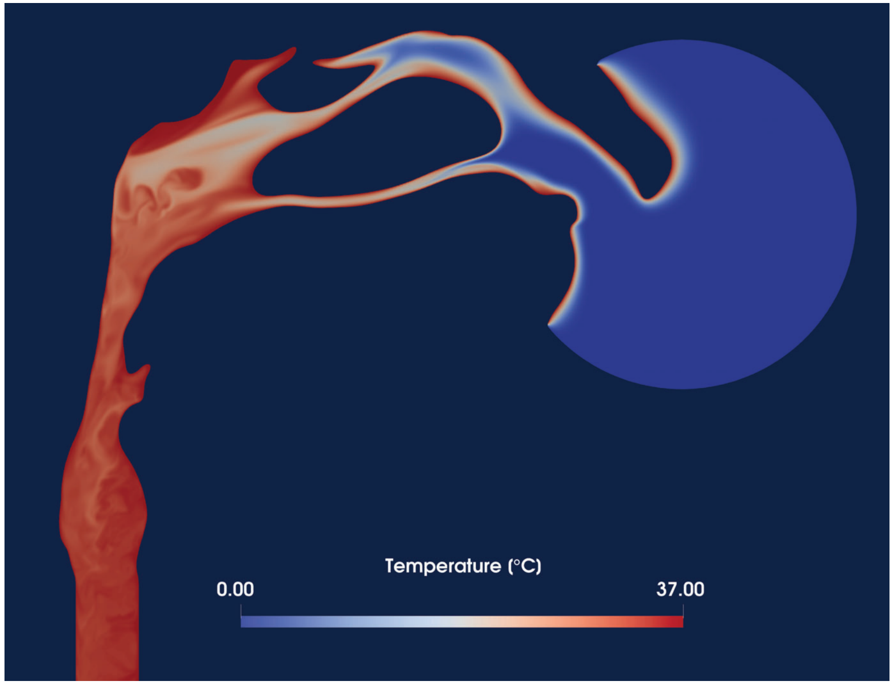
- A tree of deformations is built based on an orthogonal basis of primitive surgeries
- A number of healthy patients is given a combination of pathologies
- For ≈ 300 combinations, a hi-fi CFD solution is computed
- A neural network is trained to classify classes of pathologies
- Details in the talk by A.Schillaci, Sess.6, Thu 12:15

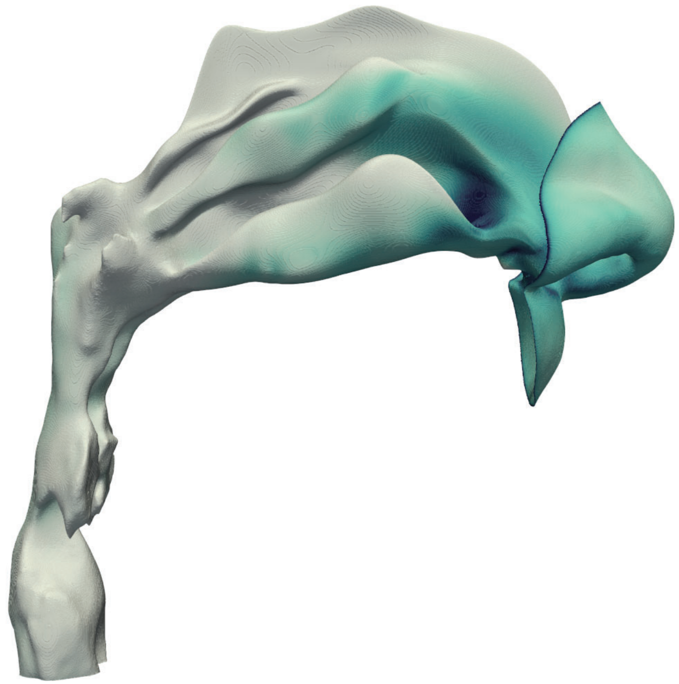
Our classifier:



Bringing physics into the picture

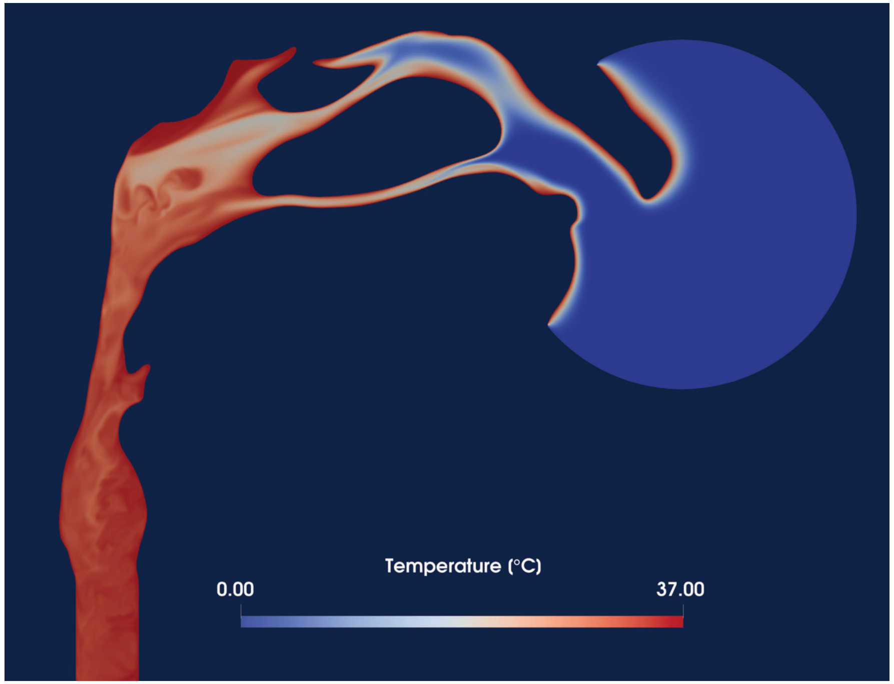
Example: warming of cold air during inhalation

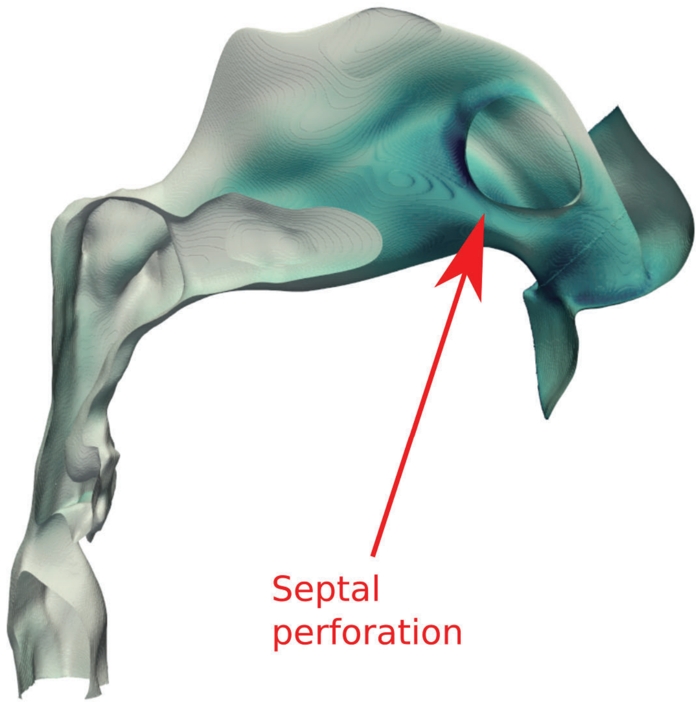




Bringing physics into the picture (physiology, but clinical importance)

Critical for septal perforations

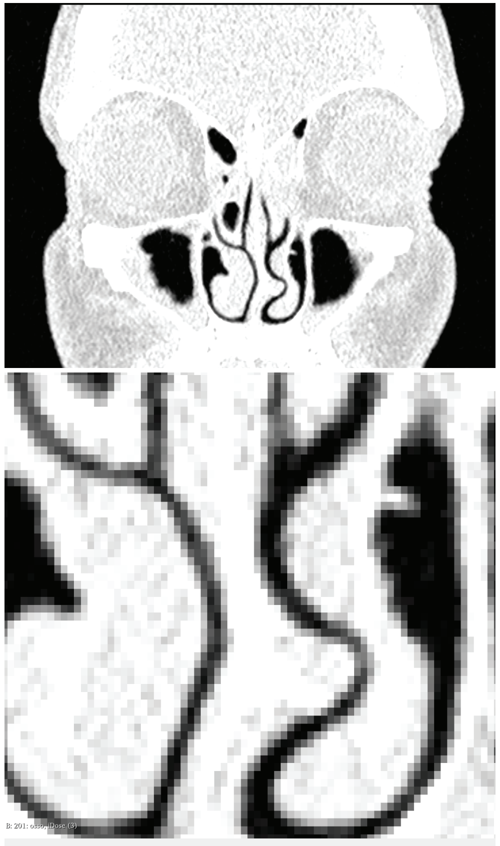




Exploiting physics to find an objective function

Geometric information is the major limiting factor

- Thickness of the nasal fossae is often 1-2 voxels (even less for pathologies)
- No less than the CT grid must be used (typically 512^3)
- Explicit reconstruction, segmentation, meshing are avoided



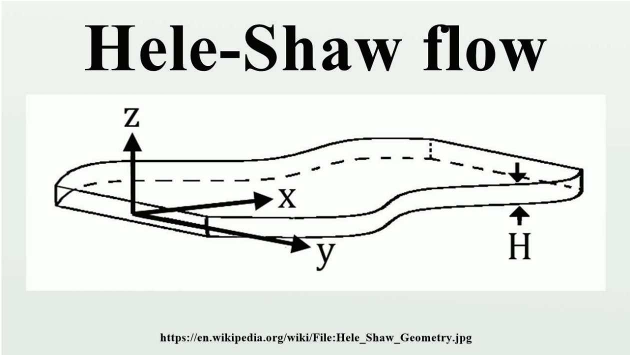
Nasal resistance is not telling the whole story

- Restoring a good Nasal Resistance is not enough
- Cfr. the ”Empty Nose Syndrome”
- Heat transfer characteristics must be also considered!

Scan of an Empty Nose

Computational speed is mandatory

- The nasal fossae are thin, non-planar channels
- Less than Navier–Stokes suffices to compute nasal resistance
- A quasi-1d approximation in the ”narrow” direction: Hele–Shaw for a non-planar channel
- Local porosity computed for each voxel as a function of the wall distance



An optimization problem (at last!)

Hypothesis: The functionally normal nose provides balanced heat transfer and hydraulic characteristics

- Analogy with heat exchangers
- An optimization problem is formulated and solved with adjoint techniques
- Lighting-fast code: 1 second on 1 core, all inclusive
- Currently under preliminary clinical test

Concluding remarks

- Active research thread with great potential
- Clinically relevant
- Highly multi-disciplinary: CFD, turbulence, modeling, flow control, numerics, shape optimization, Machine Learning, etc

Acknowledgment to the OpenNOSE gang!