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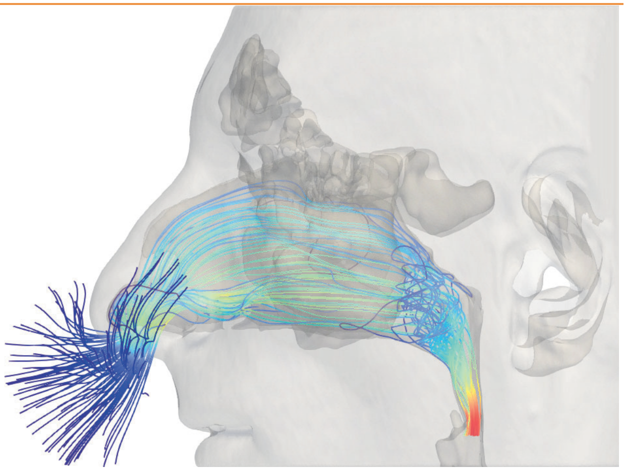
E TECNOLOGIE AEROSPAZIALI

Fluid Dynamics of the Human Nose: where flow control meets surgery

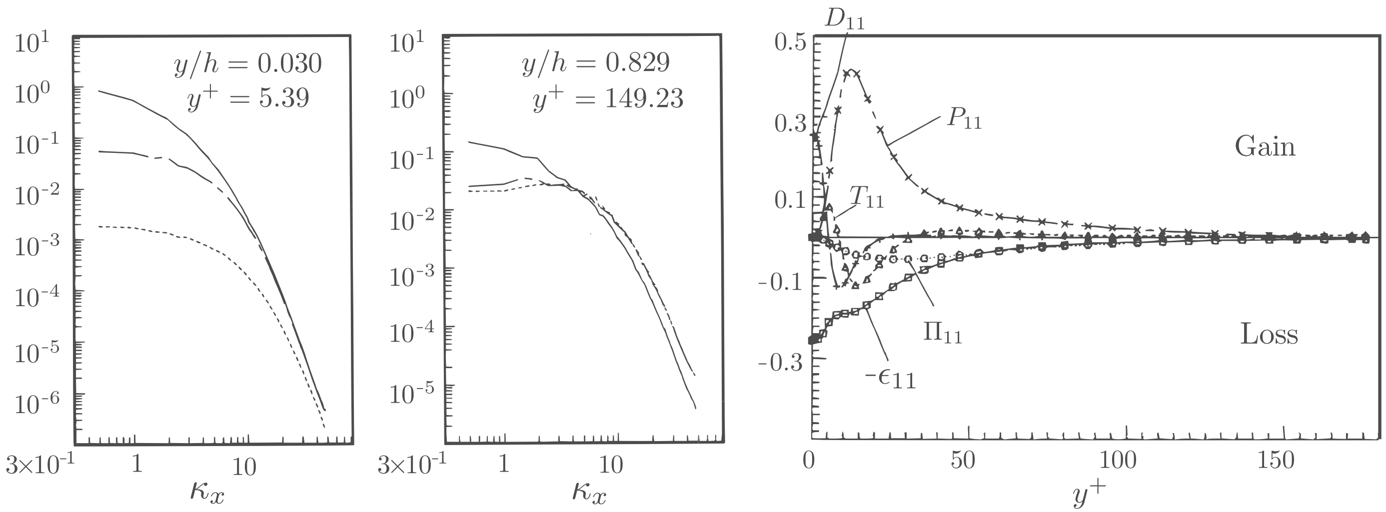
Maurizio Quadrio

UPM, Sept 8th, 2023



What this talk could have been about: (1) turbulence

The Anisotropic Generalized Kolmogorov Equations (AGKE) unite two commonly distinct viewpoints:

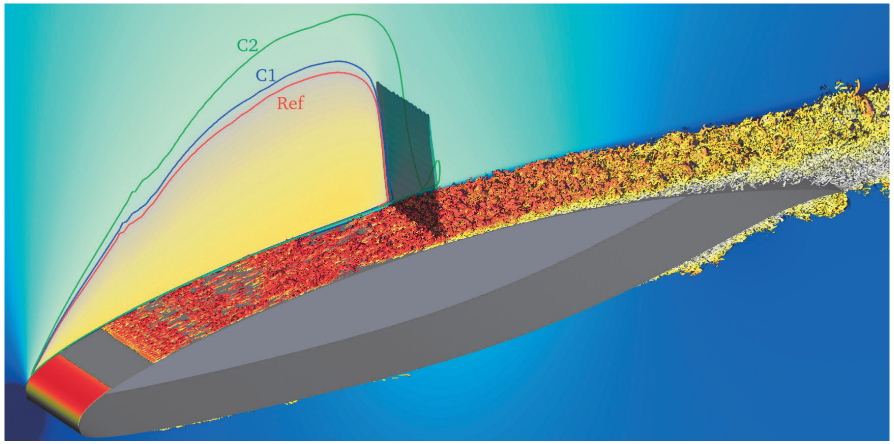


Recent phase-aware extension: φ-AGKE feature a (generic) triple decomposition

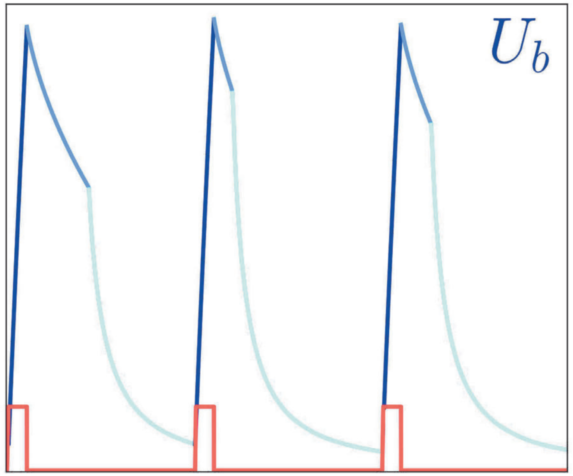
D.Gatti, A.Chiarini, A.Cimarelli & M.Quadrio, 2020. Structure function tensor equations in inhomogeneous turbulence. J. Fluid Mech. **898**, A5, pp.1–33
F.Gattere, A.Chiarini, E.Gallorini & M.Quadrio, 2023. Structure function tensor equations with triple decomposition. J. Fluid Mech. **960**, A7, pp.1–42

What this talk could have been about: (2) flow control

A localized reduction of friction might enormously impact the drag of a complex body

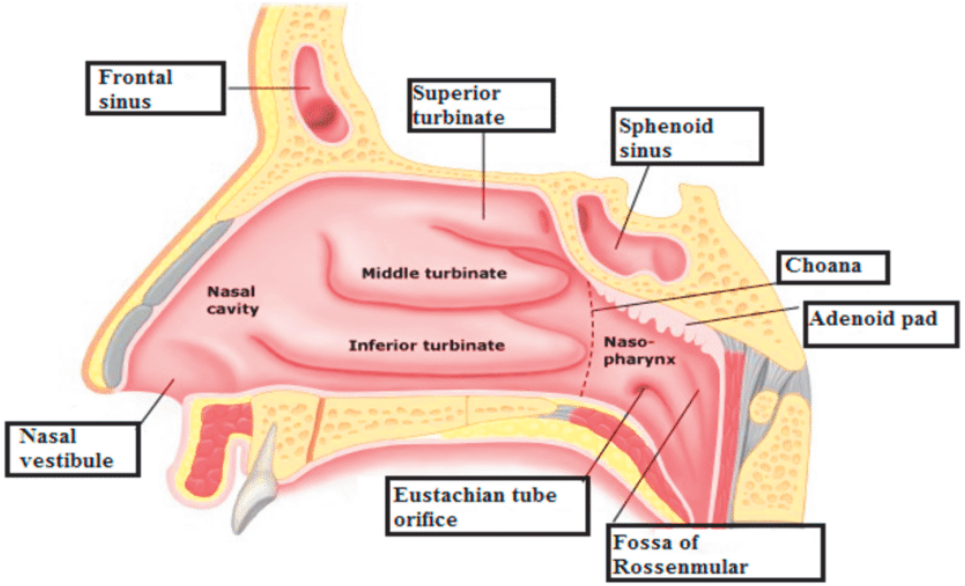


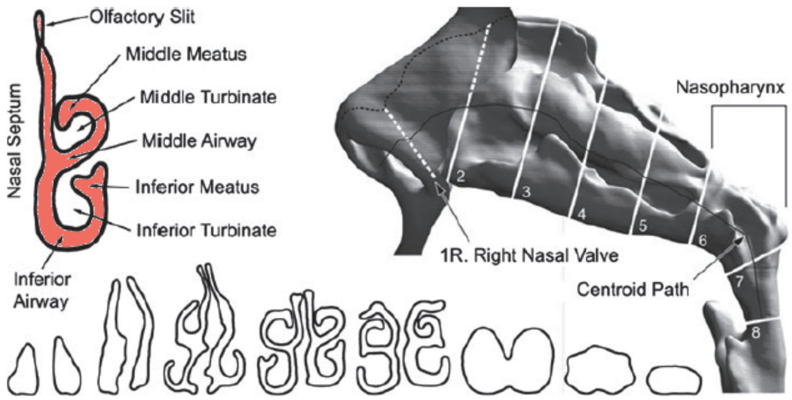
Perhaps the simplest flow control: impulsive pumping



M.Quadrio et al. 2022. Drag reduction on a transonic airfoil. J. Fluid Mech. **942**, R2
G.Foggi Rota, A.Monti, M.E.Rosti & M.Quadrio, 2023. On-off pumping for drag reduction in a turbulent channel flow. J. Fluid Mech., in press

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!

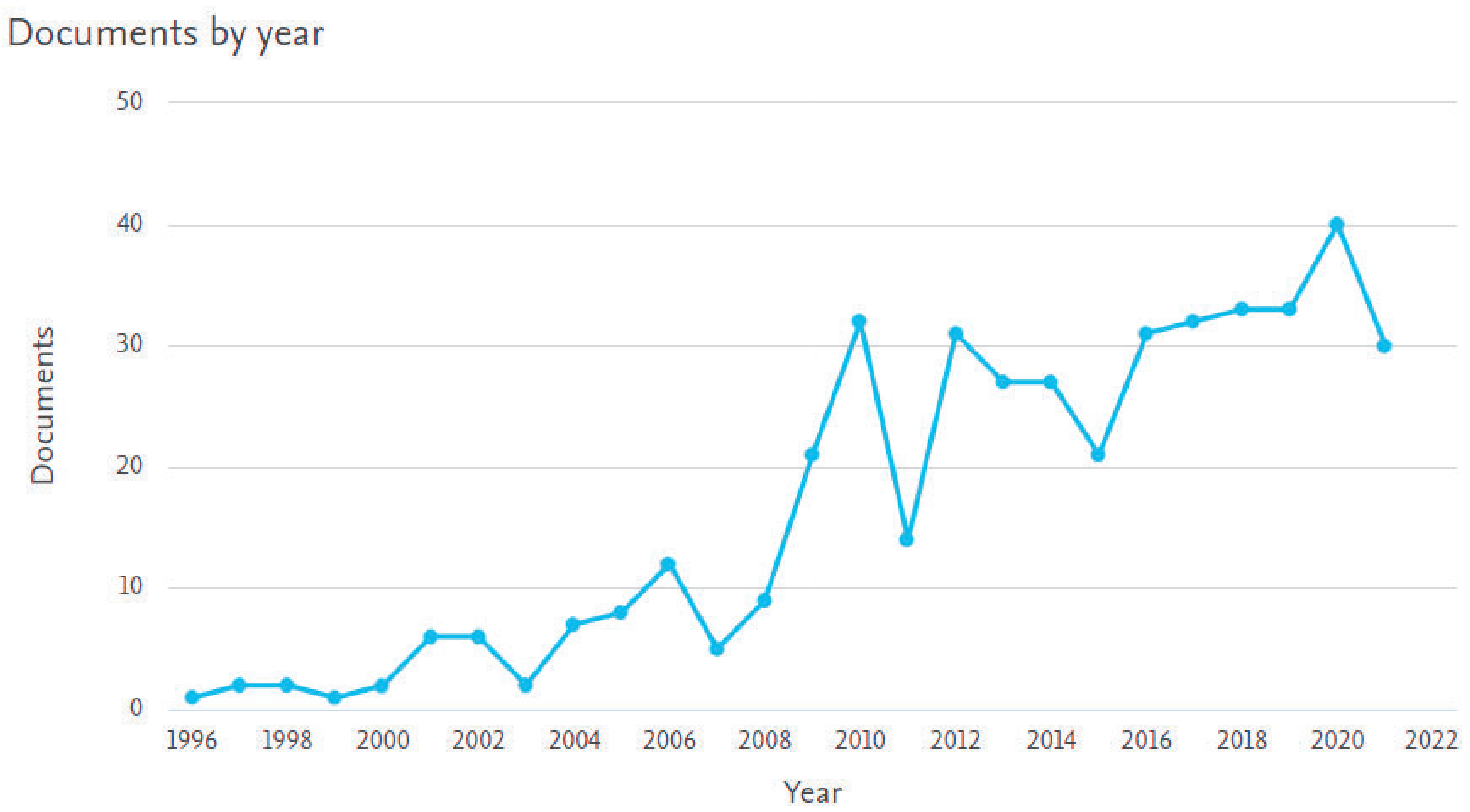
[1] Stewart *et al.* Int J Gen Med 2010

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

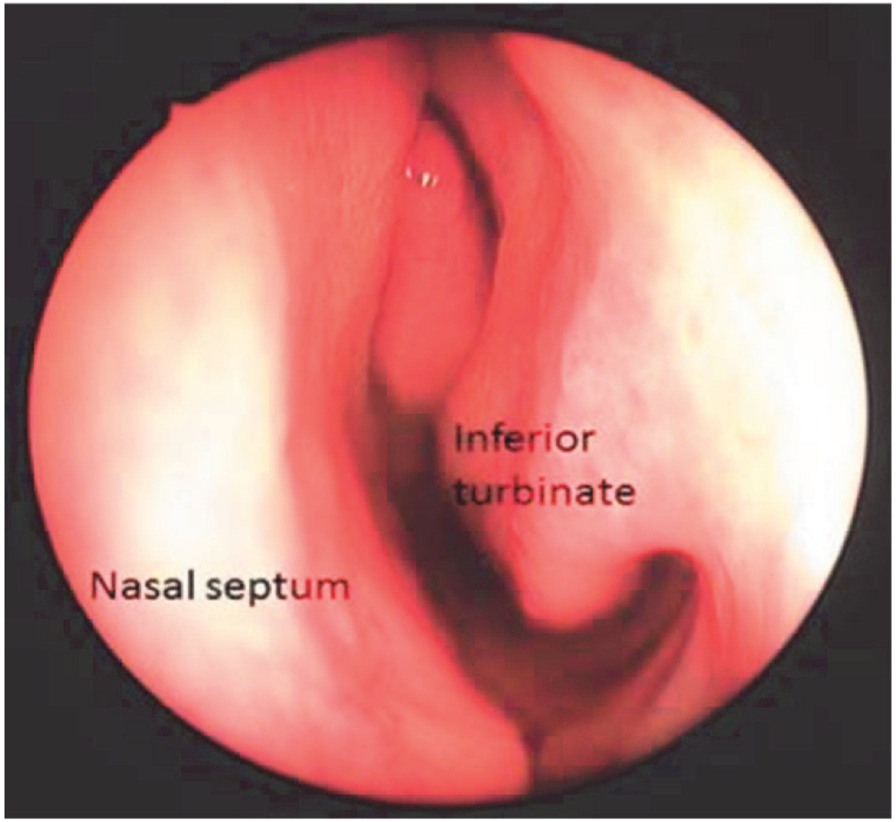
[3] Sundh & Sonnergreen, Eur Arch Otholaringol 2015

The contribution of fluid mechanics

Scopus query: ”CFD” + ”nasal”

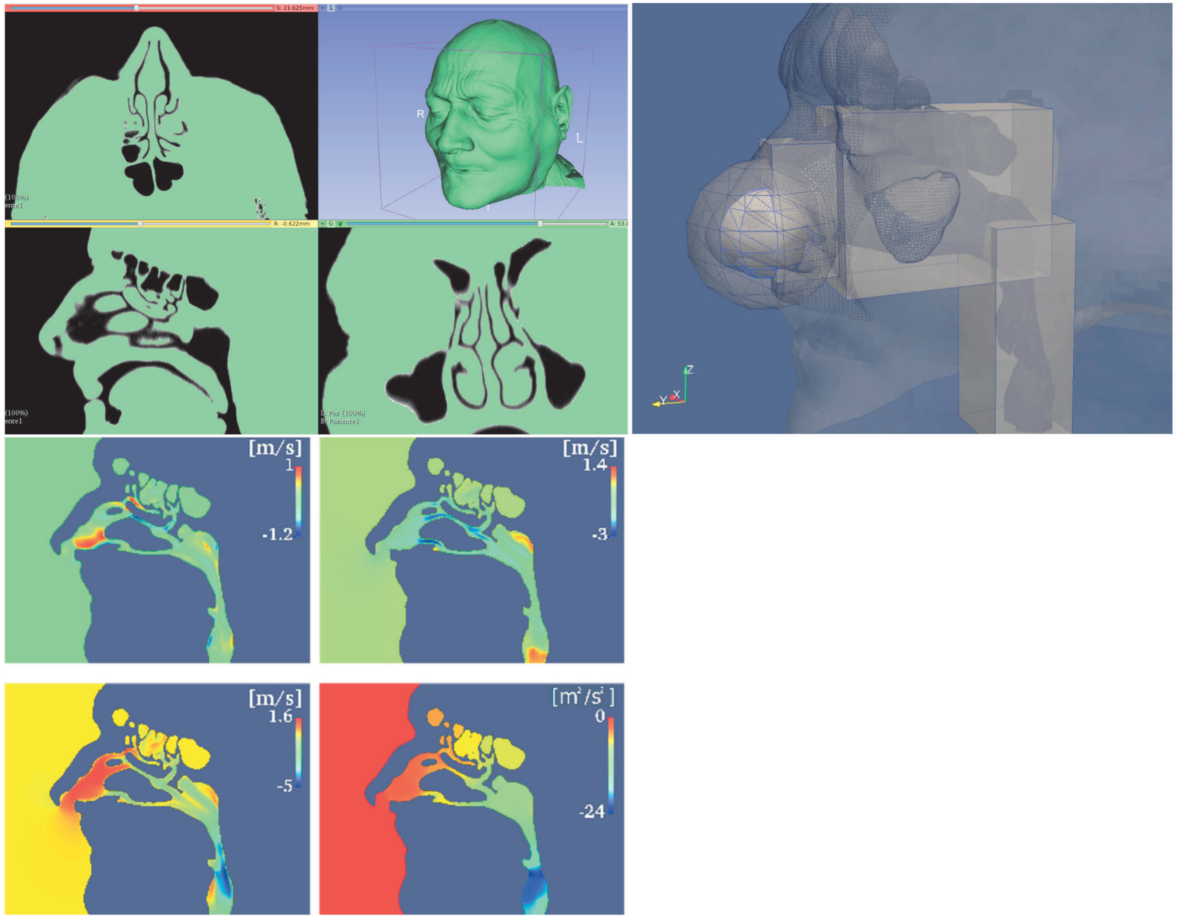


Form *and* function



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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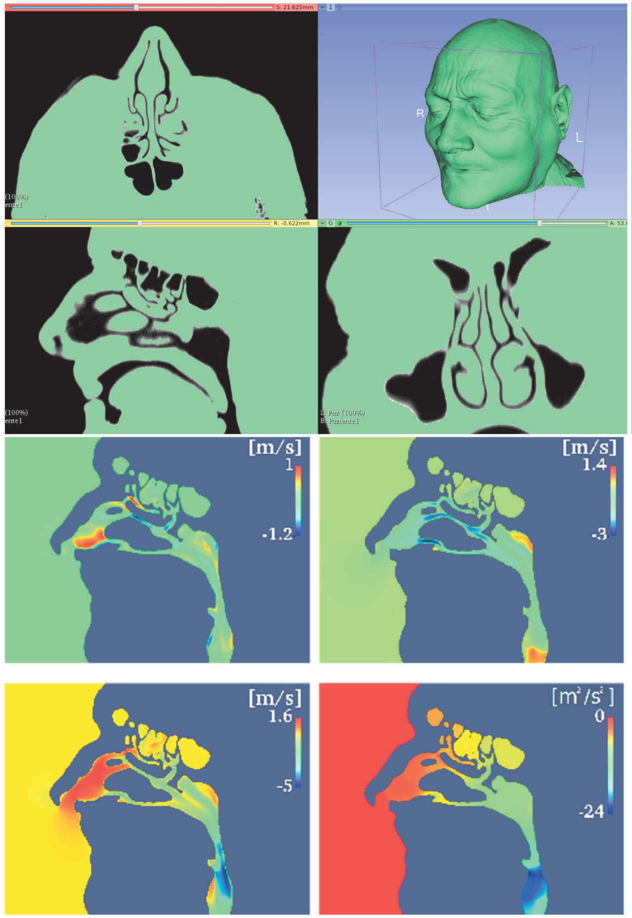
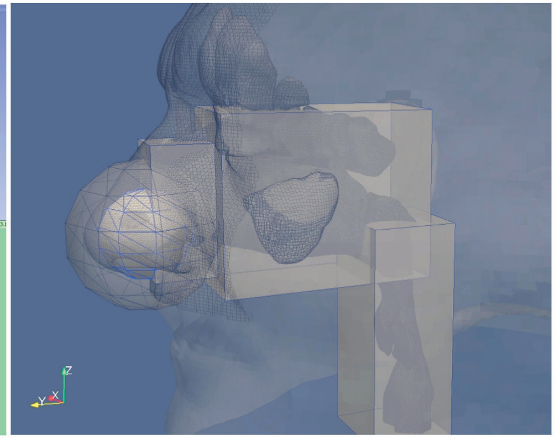
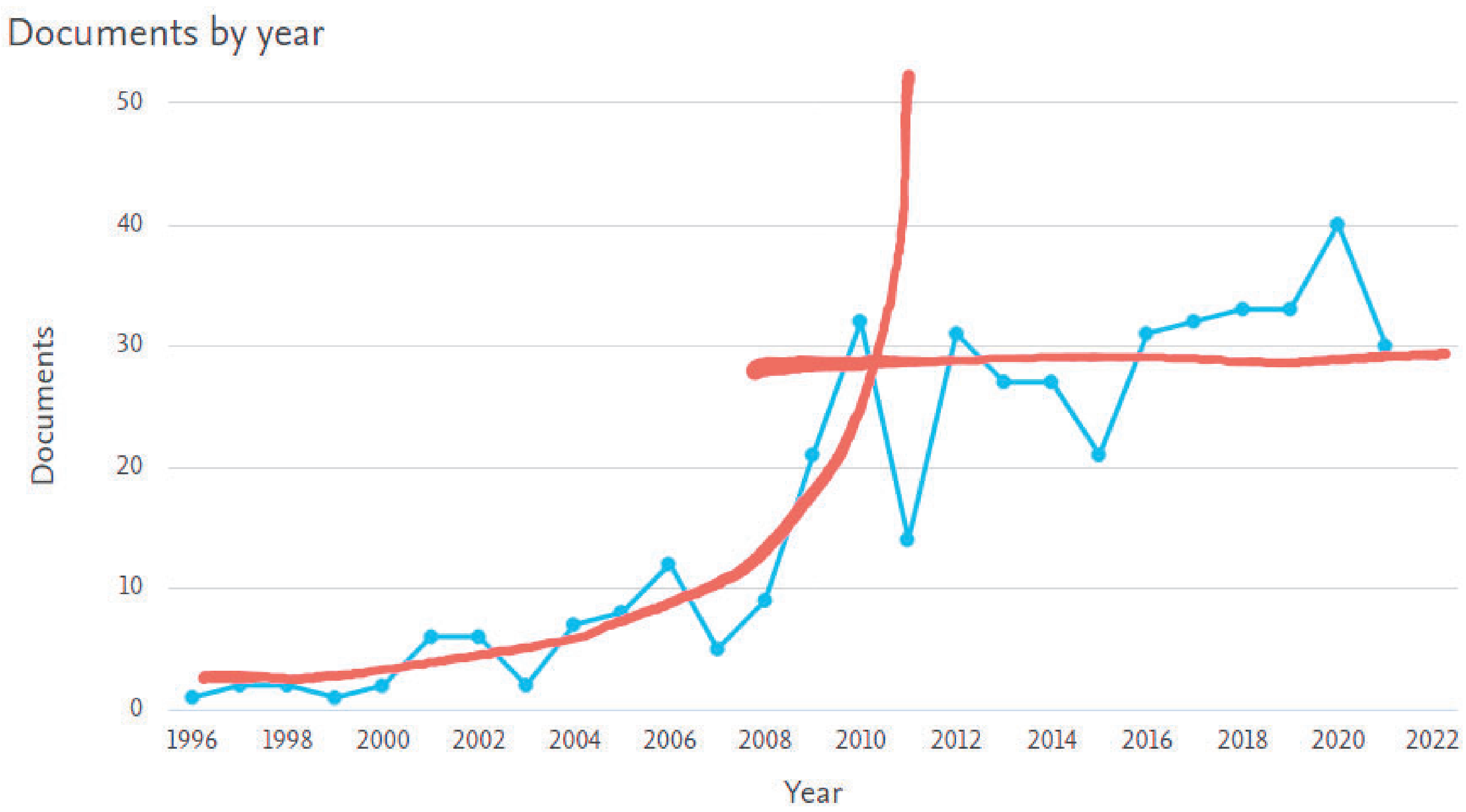




?

Only academic?

Scopus query: ”CFD” + ”nasal”



The lack of the *functionally normal* nose

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

- Reason: lack of functionally normal nose
- Shape optimization problem, but objective function is unknown
- Strong inter-subject anatomical variations with different functional significance

How to proceed?

Bringing CFD into the clinical setting requires:

1. Assess reliability through a solid benchmark
2. Distill CFD into something useful

The benchmark

Reliability

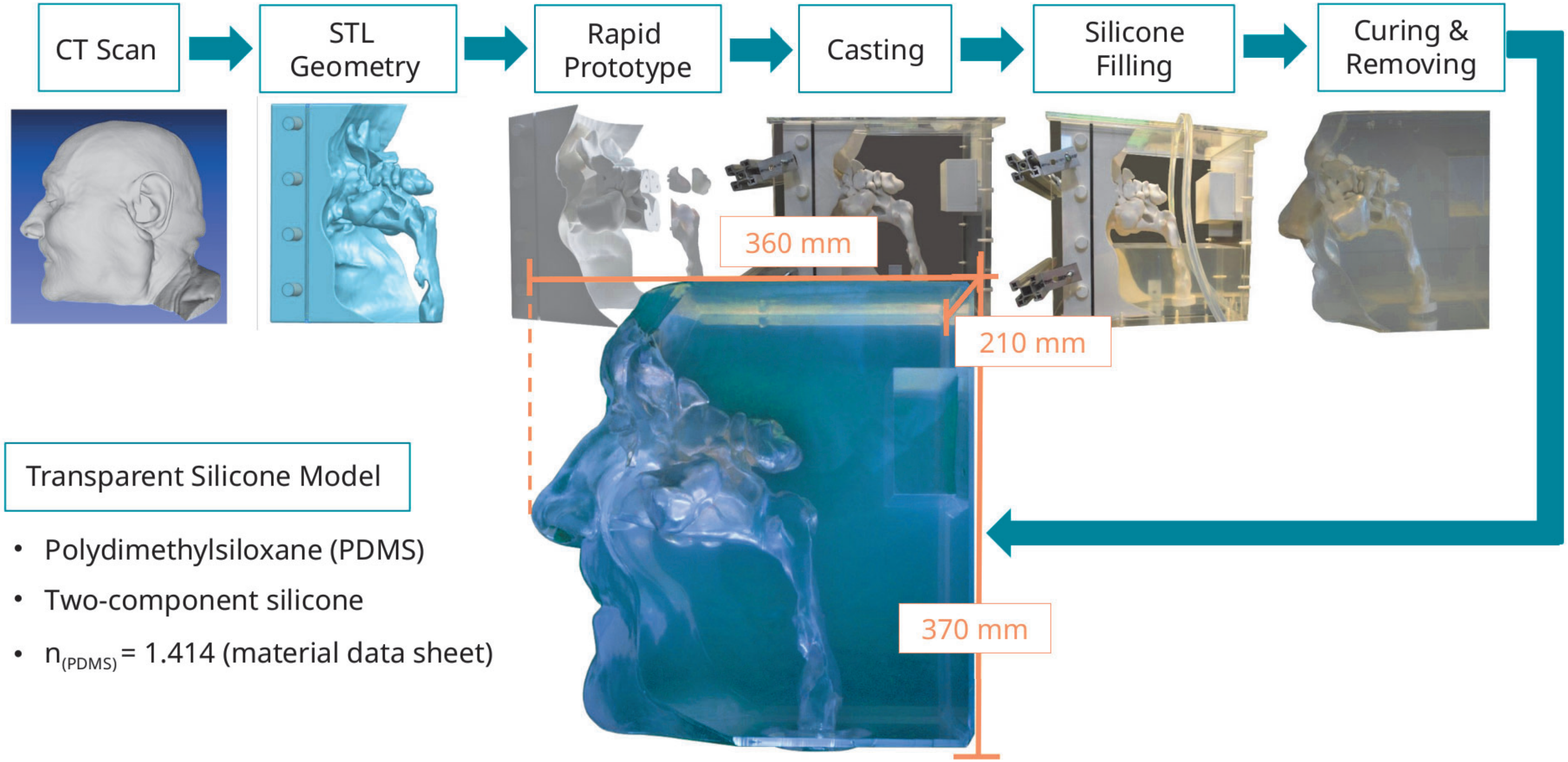
- An unique Reynolds number does not exist
- Most authors use RANS, but the flow is not turbulent
- Most authors use steady RANS, but the flow is low-*Re* and unsteady
- Accuracy of discretization is critical

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

Creating a benchmark: a tomo-PIV experiment

OSTBAYERISCHE TECHNISCHE HOCHSCHULE REGENSBURG

Transparent Silicone Model

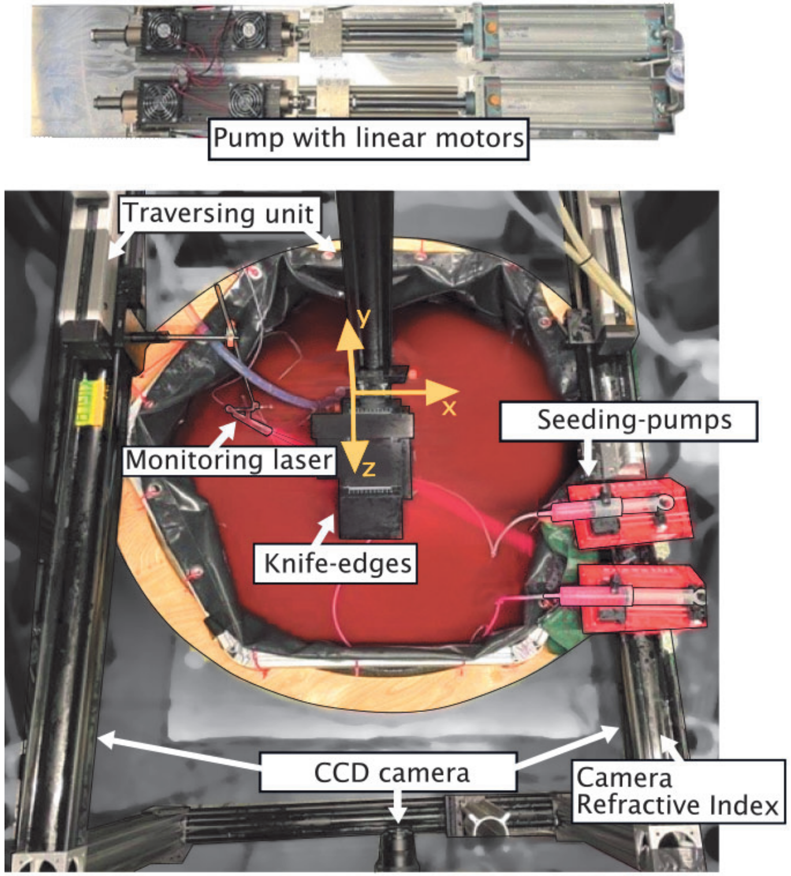


Transparent Silicone Model

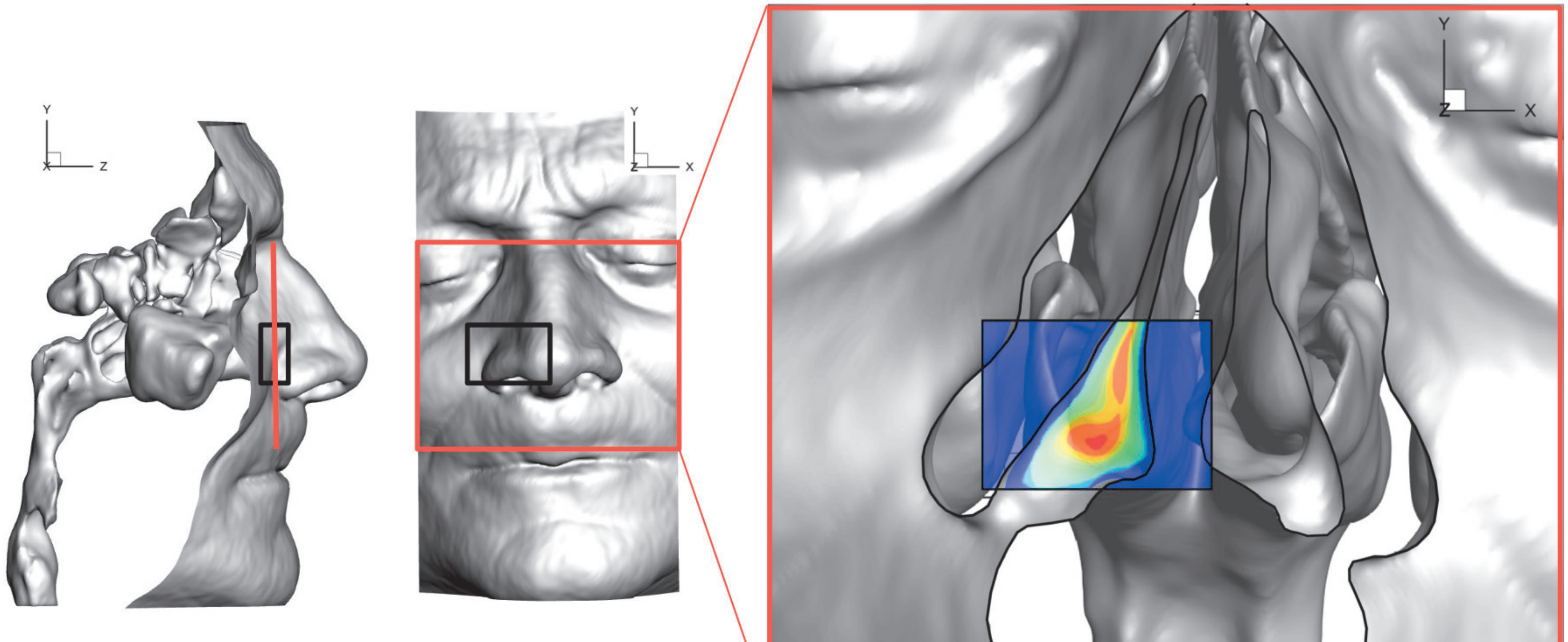
- Polydimethylsiloxane (PDMS)
- Two-component silicone
- $n_{(PDMS)} = 1.414$ (material data sheet)

The experimental setup

- 800L fish tank with 3 portholes
- 3-axis traversing unit
- CCD cameras (1600 × 1200 px) and Nd:Yag laser, 15Hz
- 2 pumps driven by linear motors
- fluorescent particles with two seeding pumps
- laser and camera for RI monitoring



Preliminary results



FoV = 49.5 mm x 36.5 mm
RoI = 49.5 mm x 36.5 mm x 4.5 mm
Scale factor = 29.1 pix/mm
VSC error < 0.1 pix

The OpenNOSE website/community

- Domain `opennose.org` registered since 2015
- Fostering the new community of *computational rhinology*
- Simultaneous availability of i) DNS data; ii) experimental data; iii) anatomy information (industrial CT scan of the phantom)

The use of CFD

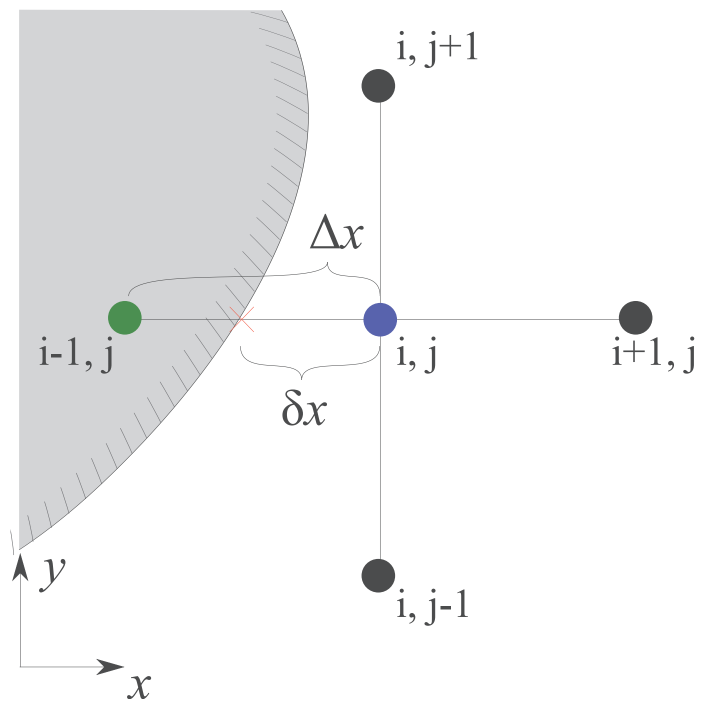
Steps to make CFD clinically viable

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

- Time
- Skills
- Money

1. An *ad-hoc* DNS solver (in CPL)

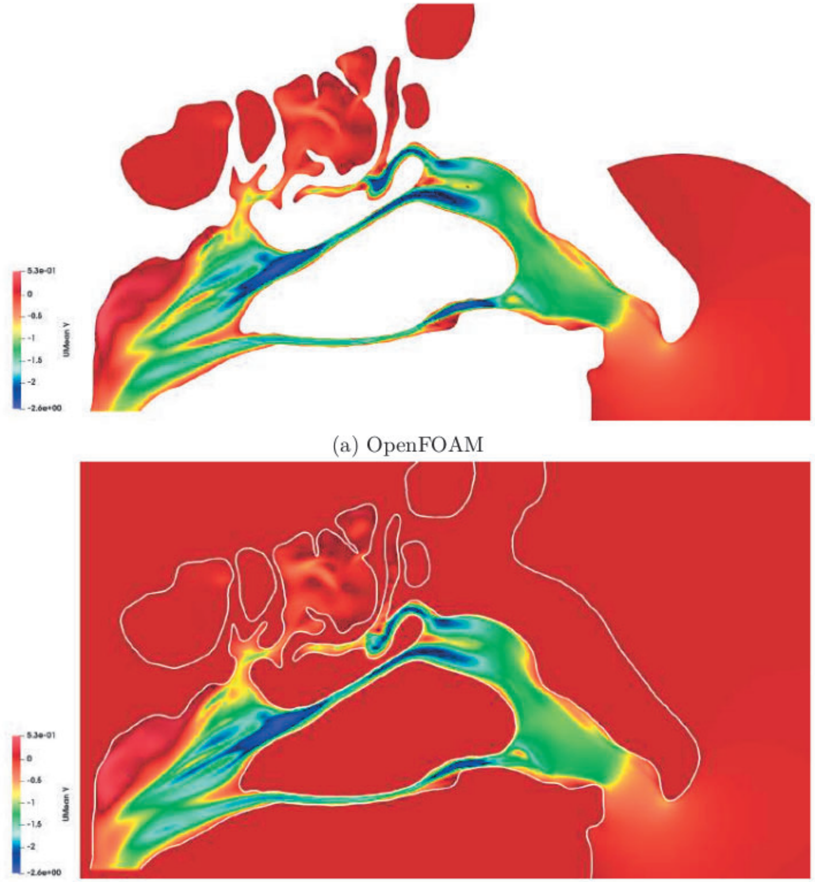
- II-order in space, staggered grid, linear extrapolation
- II-order in time but implicit (stable when grid point approaches boundary)
- Computing and storing solution at ghost nodes is not required
- Simple and efficient: it modifies the central weight of the Laplacian only
- Extrapolations in the 3 directions are independent and additive



CPL: Compiler and Programming language, `https://cplcode.net`

Testing against OpenFOAM

- STL of the nose as input
- Verified II-order convergence
- 10-100x faster than OpenFOAM
- Speed compatible with a clinical setting
- (General interest?)



(a) OpenFOAM

(b) STLIMB

2. An *ad-hoc* physical model (in CPL)

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)

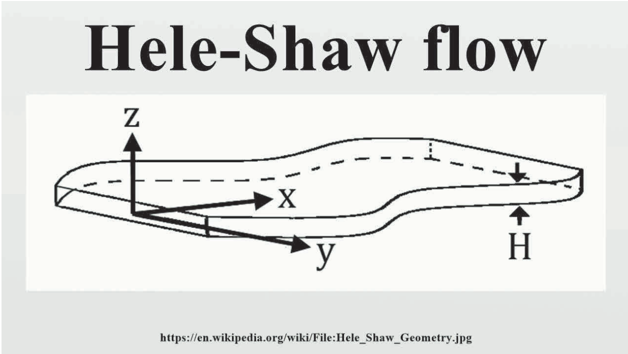
Nasal resistance is not telling the whole story

- 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

The reduced model

- 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 (with temperature)
- Local porosity computed for each voxel as a function of the wall distance
- Explicit reconstruction, segmentation, meshing are avoided



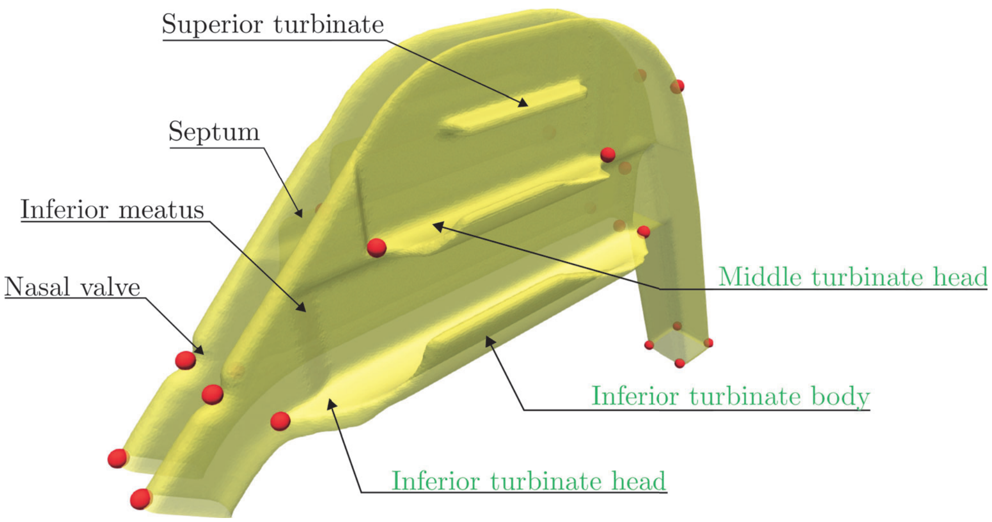
An optimization problem (at last!)

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

3. Using Machine Learning?

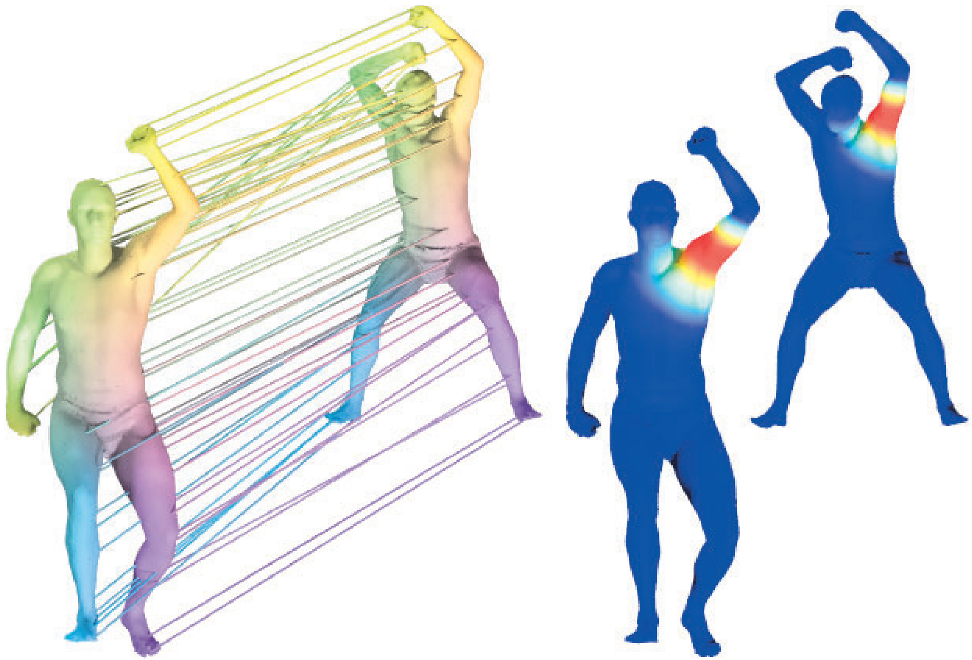
- Augment ML with CFD
- Hypothesis: the flow field amplifies anatomic information
- A simple regression problem is set up to test the hypothesis
- Parametric, CAD-based model nose with 4 pathological parameters
- Regression performance is compared for geometric- vs flow-based features



The way we derive features

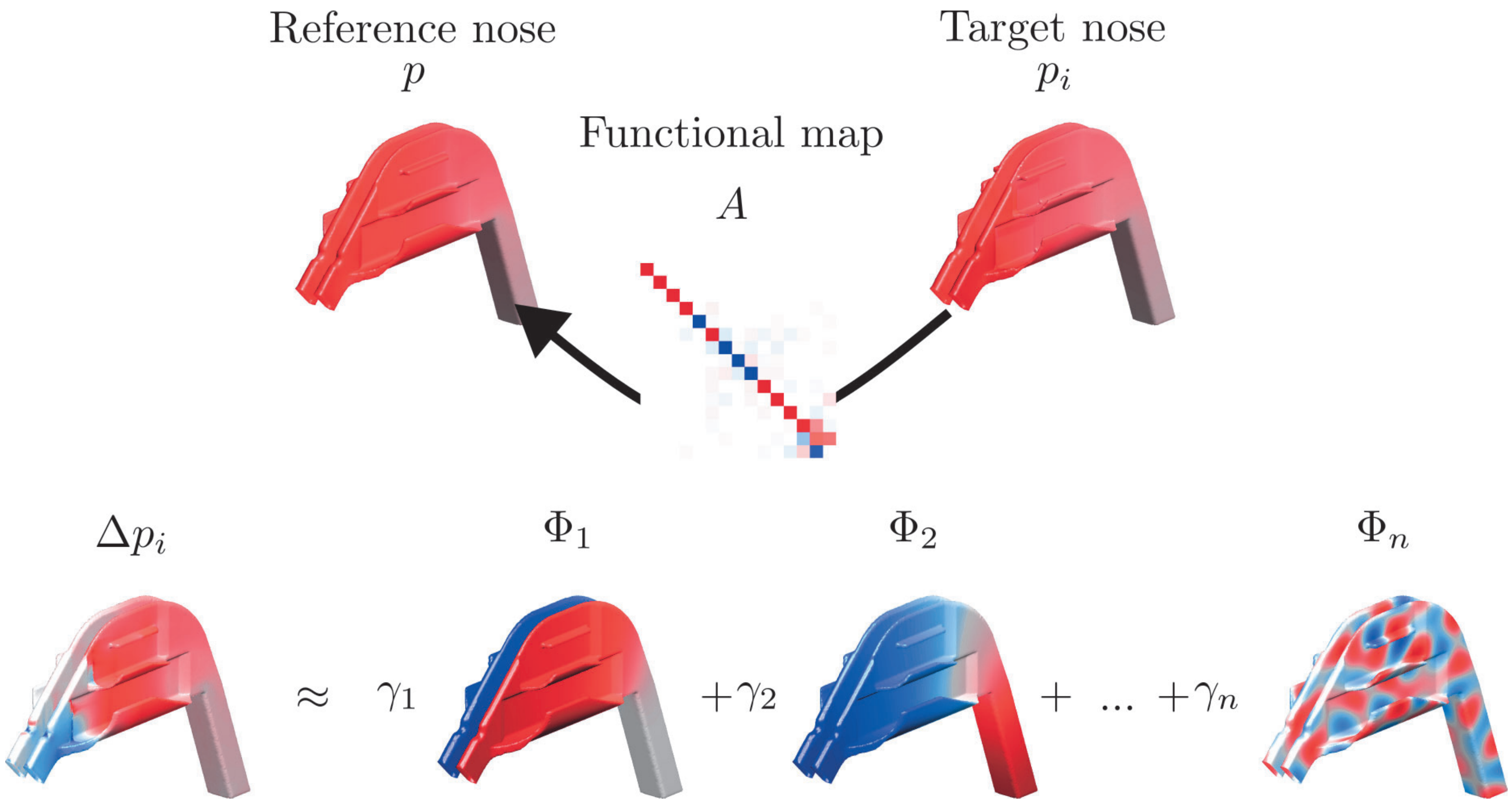
Features are computed with functional mapping[a] (FM)

- tool from computational geometry
- expresses bidirectional mapping between two shapes (and functions defined over them)

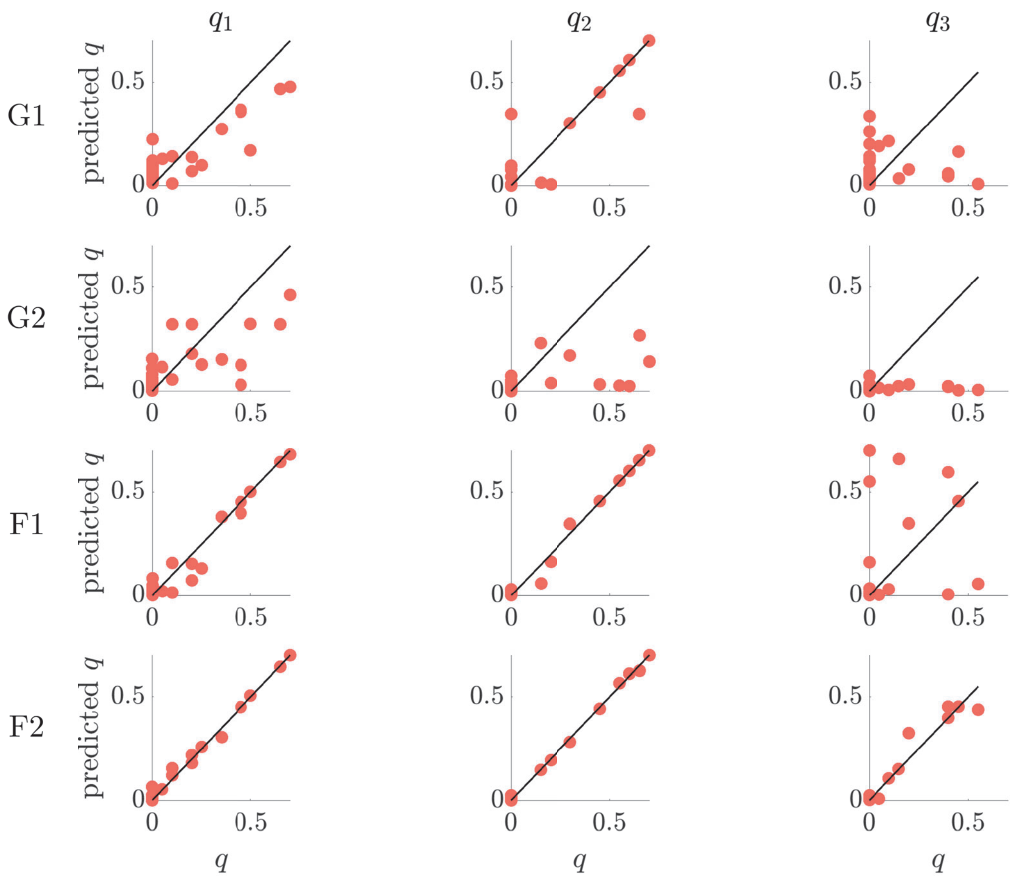


[a] M.Ovsjanikov *et al.* ACM Trans. Graph. 2012

An example of flow-based feature



F-features are superior to G-features

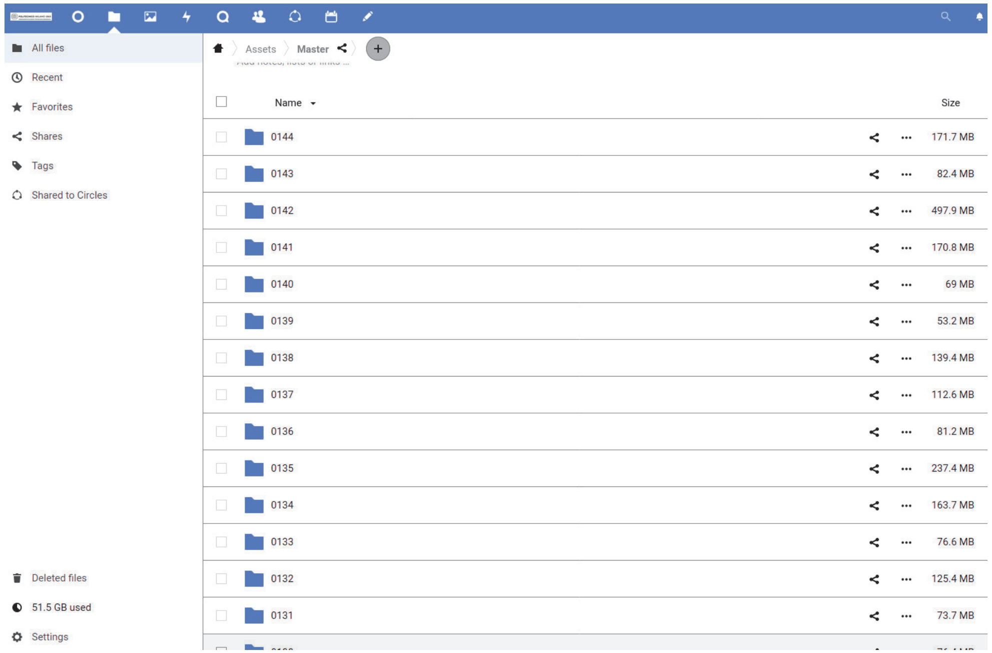


4. Using Machine Learning!

Database of:

- CT scans
- rhinomanometry data
- ENT evaluation sheet

Open and labeled data: huge value!

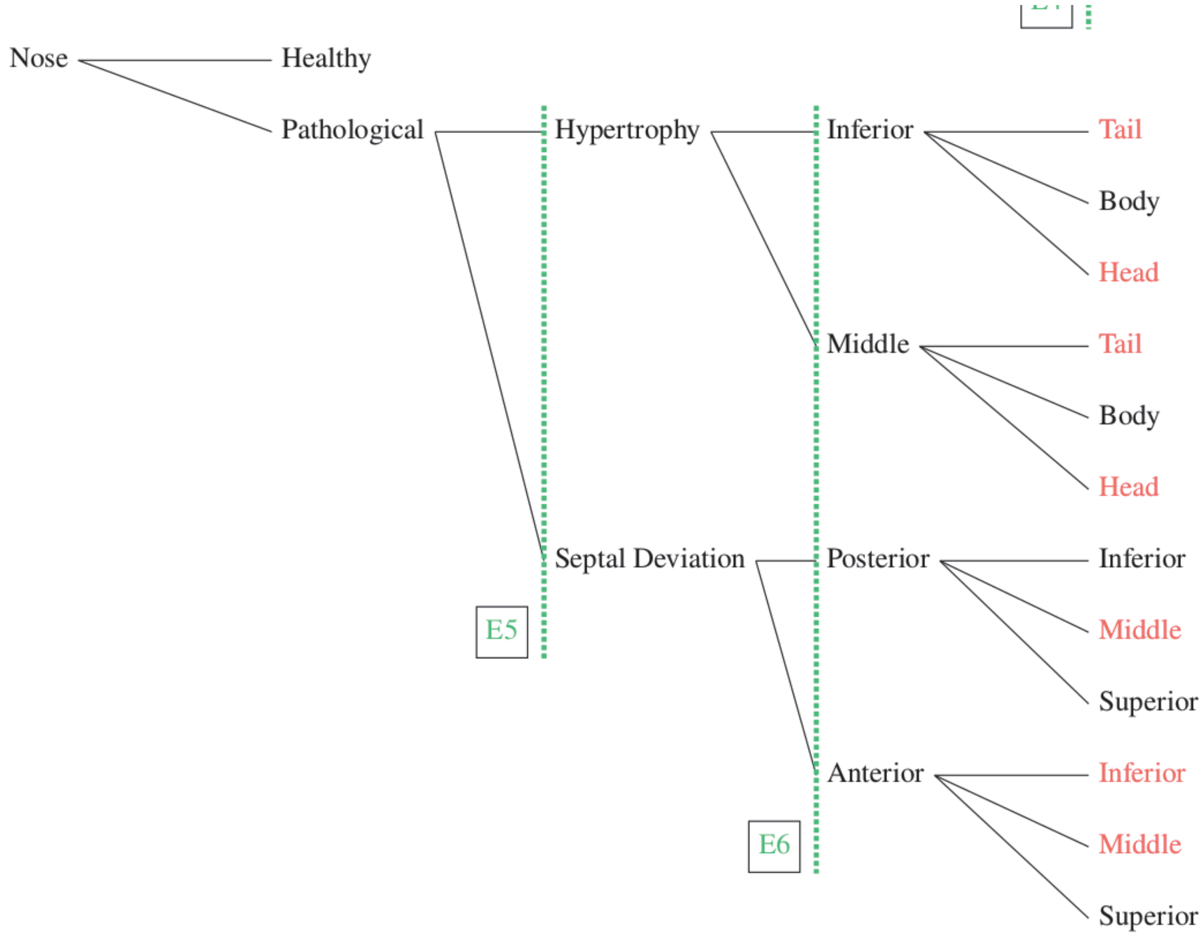


CFD-augmented ML

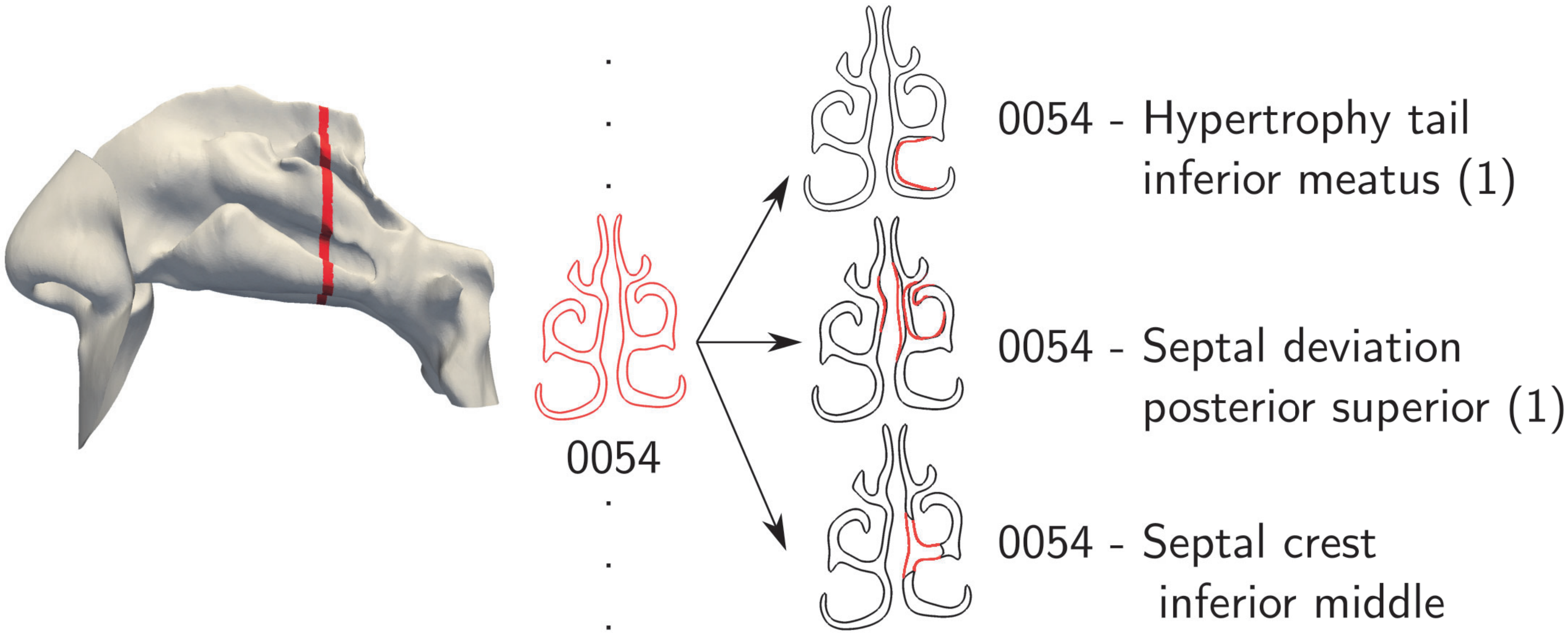
Augmenting ML with CFD (not the other way around) is new and poses new problems

1. Univocal training data are needed
2. The dimensionality of the CFD output is much larger than the allowed ML input

Step 1. Define a tree of elementary defects

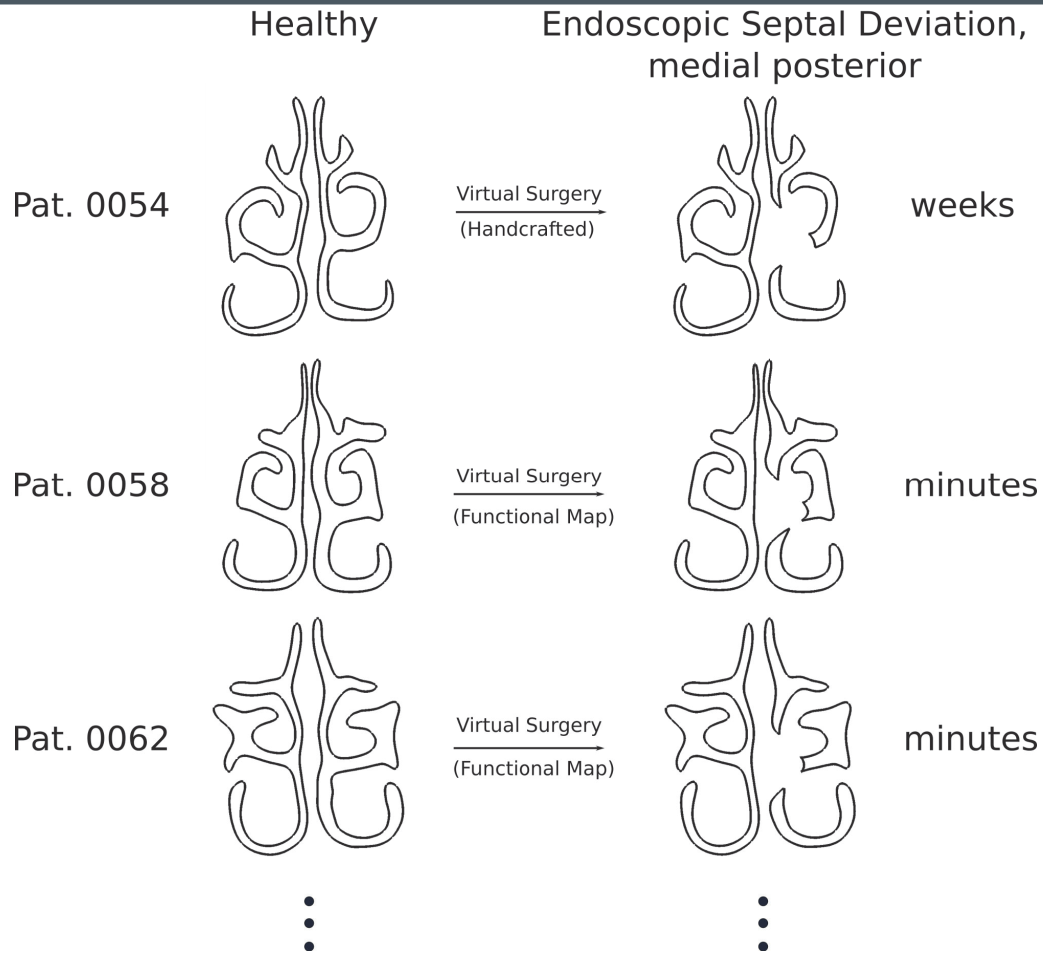


Step 2. Create atomic defects via virtual anti-surgeries



Step 3. Transfer defects with functional maps

- On a first healthy patient, realistic deformations are created by hand (time: weeks)
- Deformations are applied to other healthy patients via functional maps

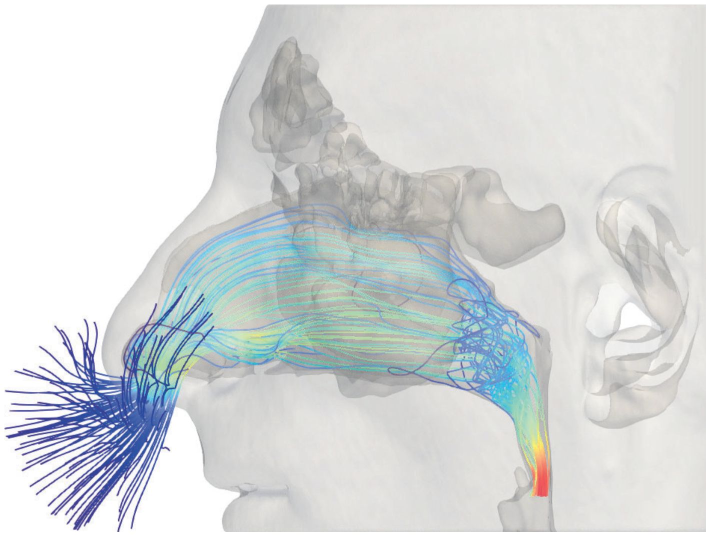


Step 4. Run CFD to create the database

- 277 distinct anatomies are generated from 7 healthy patients
- Defects are isolated or in combination, various severities
- Classes are relatively balanced (but for the healthy class)
- OpenFOAM is used to compute the flow field

The OpenFOAM setup

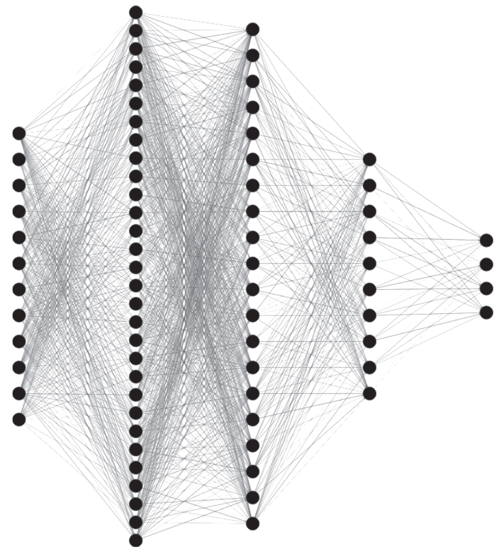
- Steady inspiration at 280 ml/s (mild breathing)
- Well resolved (incompressible) LES
- Mesh with 15M cells, no layers, $\nu_t/\nu < 4.4$
- All terms at second-order accuracy
- Statistics computed over 0.6 s
- 7000 core hours for each case



A neural network to classify pathologies

- A standard neural network is trained to classify pathologies
- Three fully-connected hidden layers (30, 20, 10 neurons each)
- Hyperbolic tangent as activation function (sigmoid for output); cross-entropy as loss function; scaled conjugate gradient as backpropagation algorithm to update weights and biases
- LOO-CV (preferred to *k*-fold CV) as partition method to carry out validation and testing

Our classifier (12 inputs, 4 outputs):

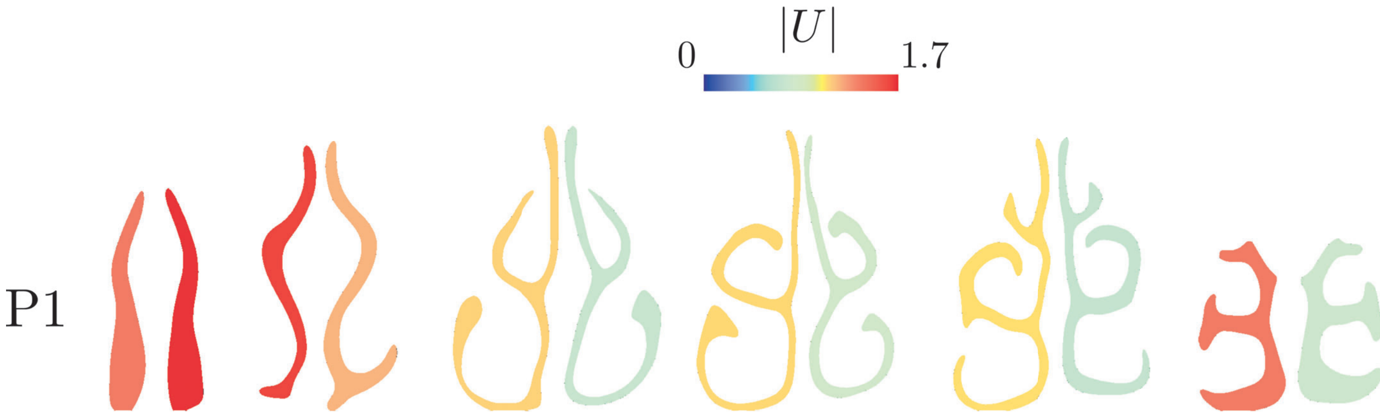


Converting CFD to a small feature set

The number of inputs to the NN must be small (as such is the number of observations)

Manual feature extraction

Two strategies: regional averages (of velocity, vorticity, TKE, strain, pressure, pressure gradient, etc), and line integral over streamlines

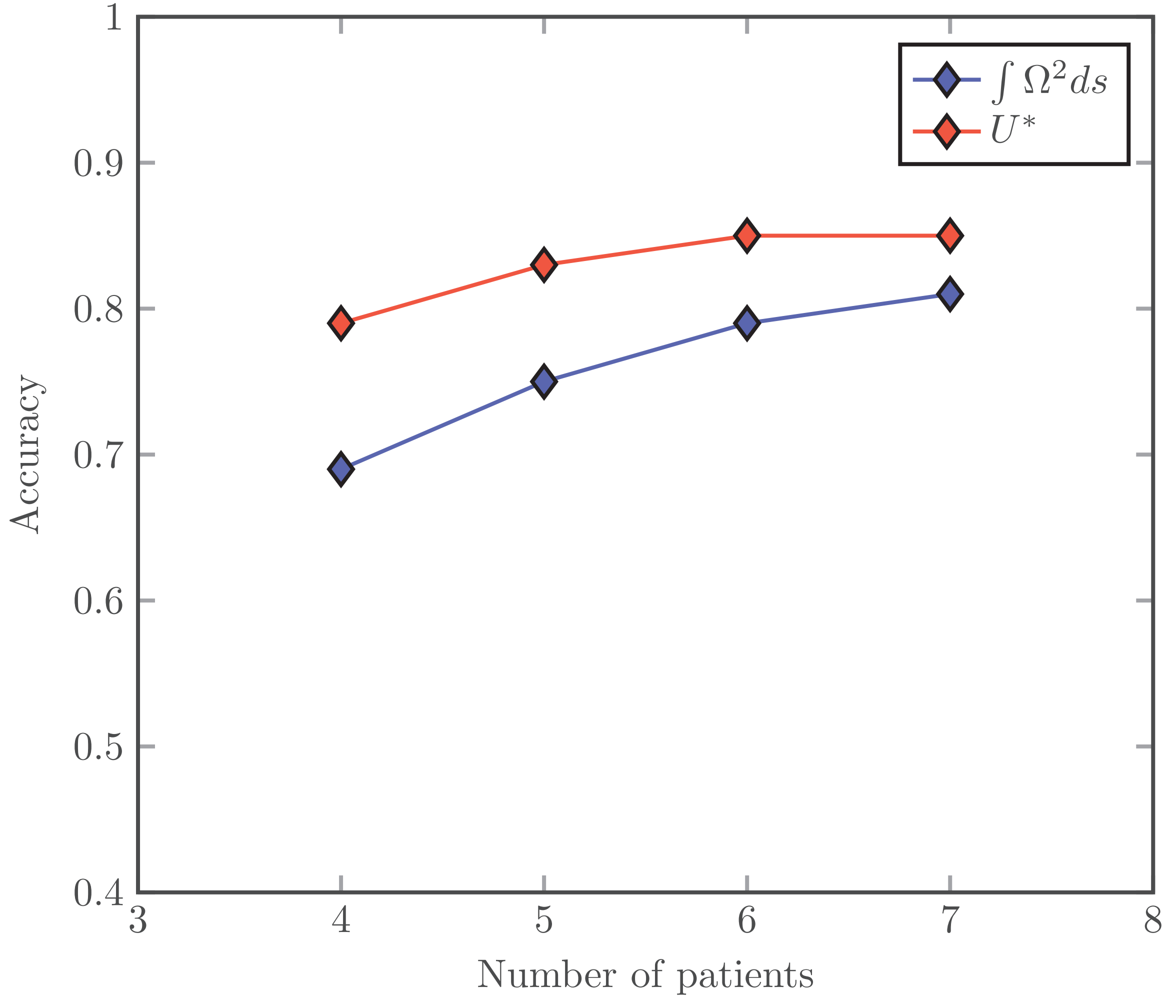


Results: classification experiment (four classes, LOO)

Class	accuracy	precision	recall	F1
Anterior septal deviation	0.91	0.82	0.91	0.86
Posterior septal deviation	0.90	0.30	0.11	0.16
Middle turbinate hypertrophy	0.67	0.47	0.51	0.49
Inferior turbinate hypertrophy	0.71	0.51	0.51	0.51

- With k-fold CV accuracy approaches 100%
- Adding simple features improves accuracy further

The dataset needs to grow further



Concluding remarks

- The nose flow is an interesting, high-potential interdisciplinary topic
- CFD-augmented ML techniques are promising
- CFD (and HPC to some extent) has a bright future in medicine

Acknowledgment to the OpenNOSE group!