



POLITECNICO
MILANO 1863

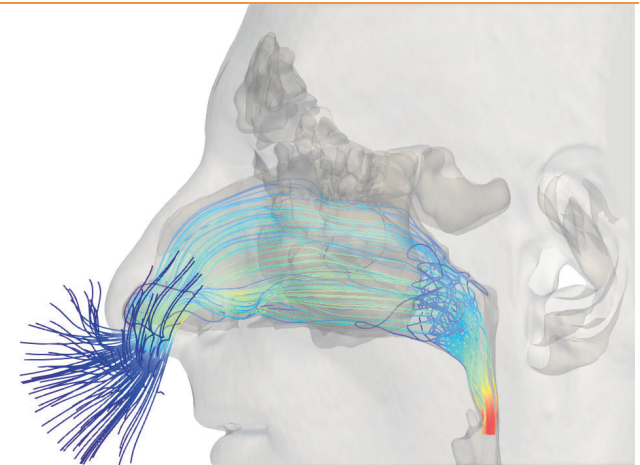
DIPARTIMENTO DI SCIENZE
E TECNOLOGIE AEROSPAZIALI

The flow in the human nose

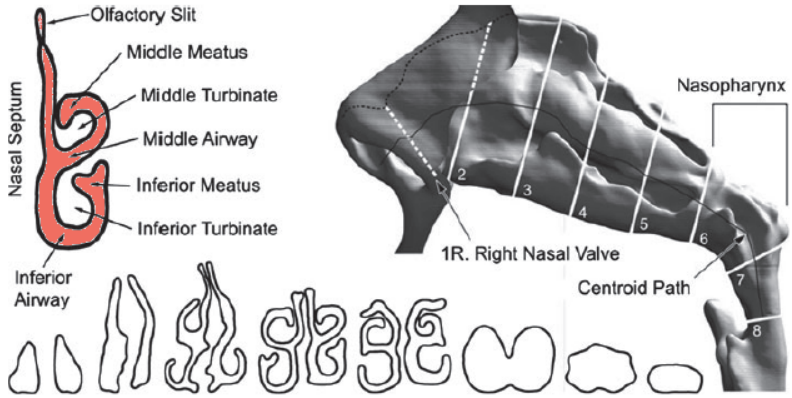
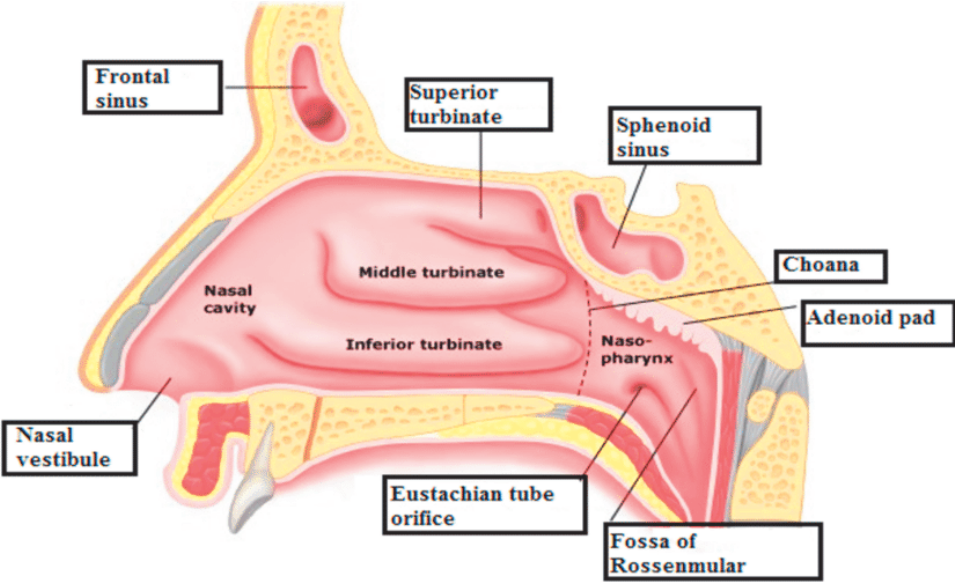
CFD, surgery and flow control

Maurizio Quadrio

Genova, Dec 11, 2025



The human nose: form and function(s)



Is the nose flow important?

- ▶ At least 1/3 of the adult world population is troubled with nasal breathing difficulties¹
- ▶ In 2014, the one-year (only) cost of chronic rhinosinusitis (alone) in US (only) was \$22bn²
- ▶ Certain nose surgeries have 50% failure rate³

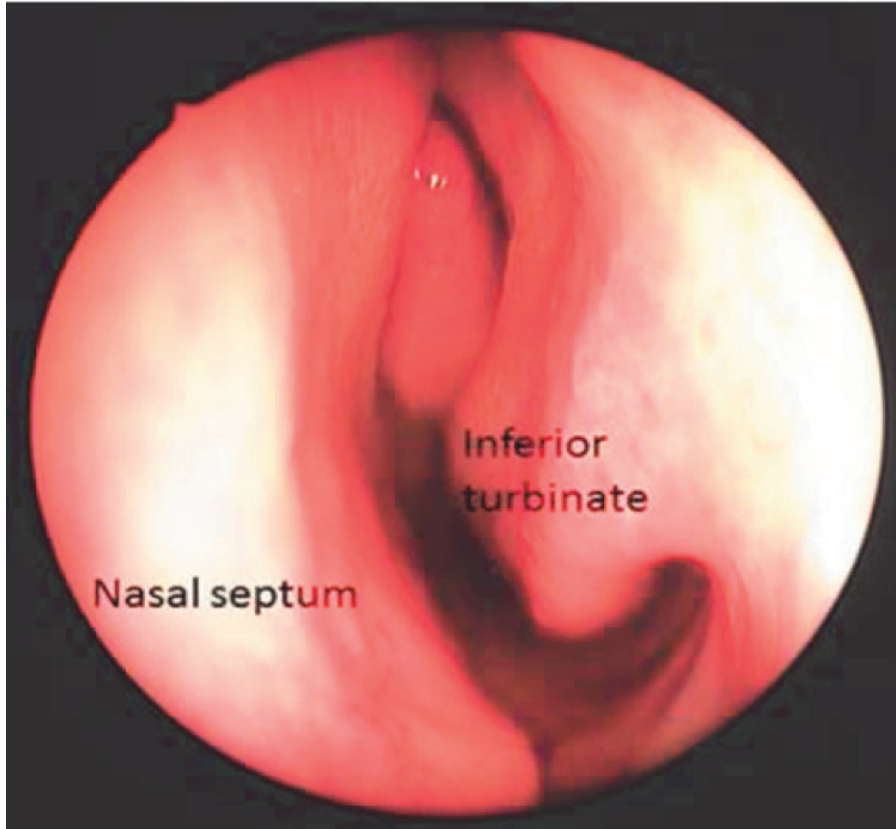
Huge room for improvement!

¹ Stewart *et al.* Int J Gen Med 2010

² Smith *et al.* The Laryngoscope 2015

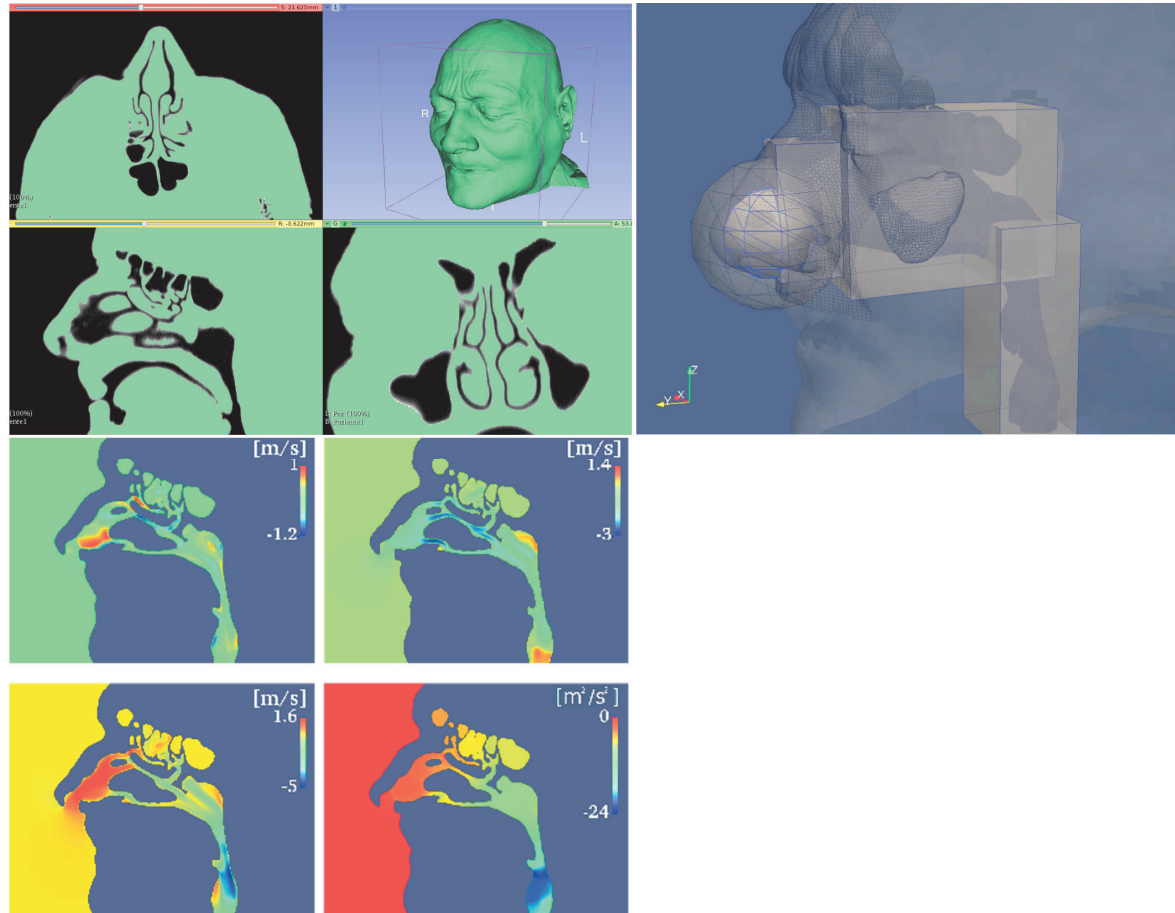
³ Sundh & Sonnergreen, Eur Arch Otolaryngol 2015

Form and function



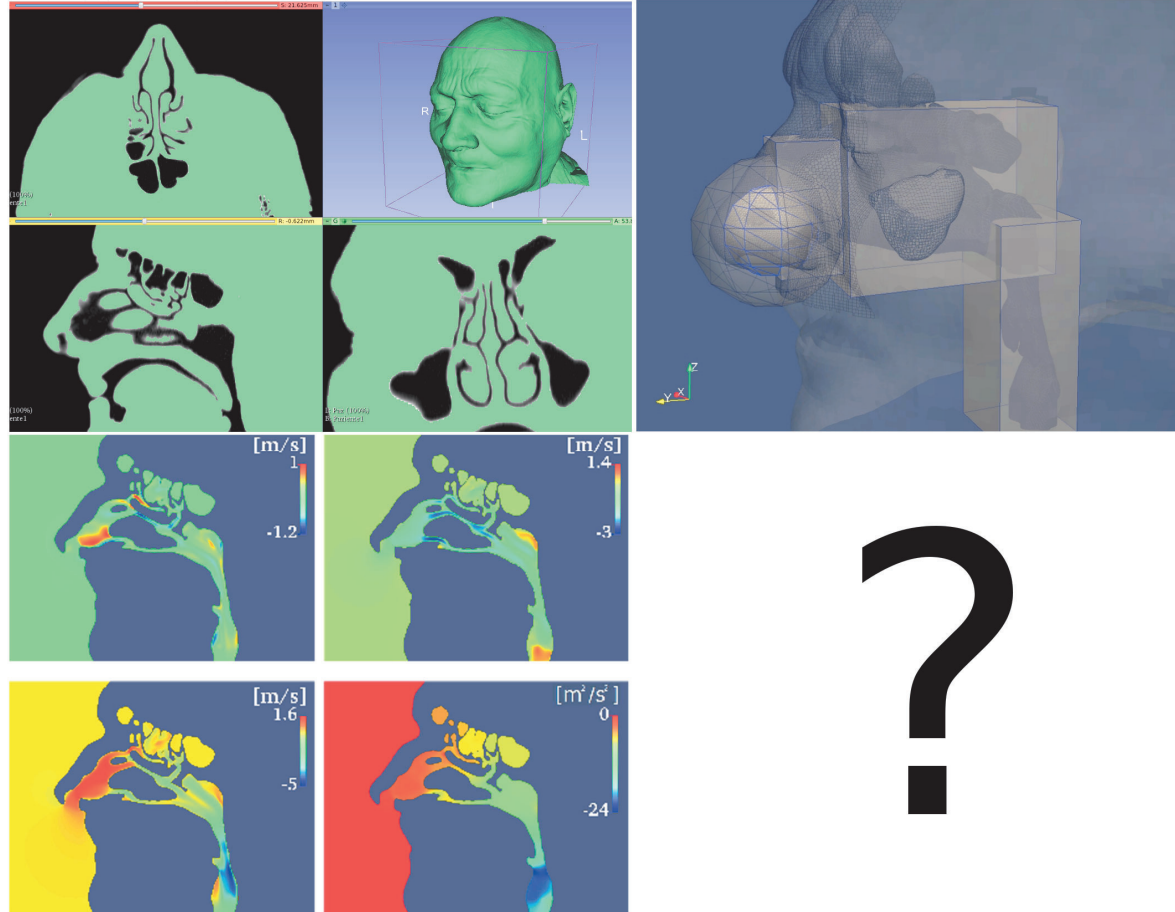
The workflow: from CT scan to...

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



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4. Then what??



The lack of the **functionally normal** nose

- ▶ Strong inter-subject anatomical variations with different functional significance
- ▶ Link between form and function is mediated by the **non-linear** Navier–Stokes equations
- ▶ Shape **optimization** problem, but **objective function** is unknown

Let's address the "?"

Bringing CFD into the **clinical** setting requires:

- ▶ Improving reliability
- ▶ Distilling CFD into something **useful**

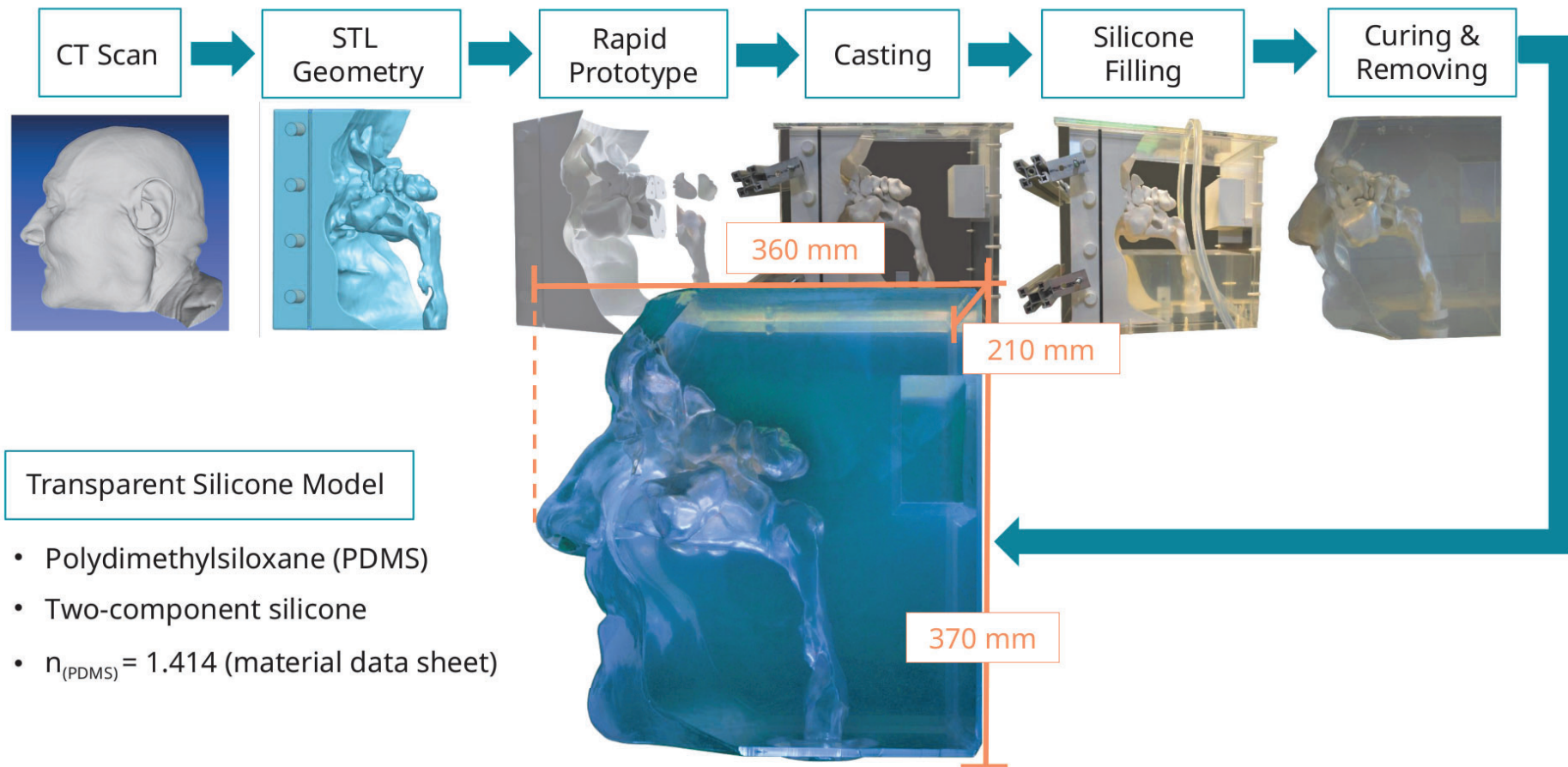
Reliability

- ▶ 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

Transparent Silicone Model



The OpenNOSE website/community

- ▶ Domain `opennose.org` (registered since 2015)
- ▶ Simultaneous availability of i) experimental data; ii) DNS data; iii) anatomy information (CT scan of the phantom)

Ad-hoc CFD tools

Current CFD is not clinically viable

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

- ▶ Time
- ▶ Skills
- ▶ Money

Introducing AMPHIBIOUS, the DNS solver

A MultiPlatform High-performance Immersed-Boundary
Incompressible Open-soUrce Solver

- ▶ Immersed-boundary method
- ▶ Iterative pressure correction
- ▶ Domain decomposition based on the building-cube method^a
- ▶ Written in CPL <https://cplcode.net>, runs on CPUs and GPUs

^aN.Jansson et al, CUBE: a scalable framework for large-scale industrial simulations, Int J High Perf Comp Appl, 2018

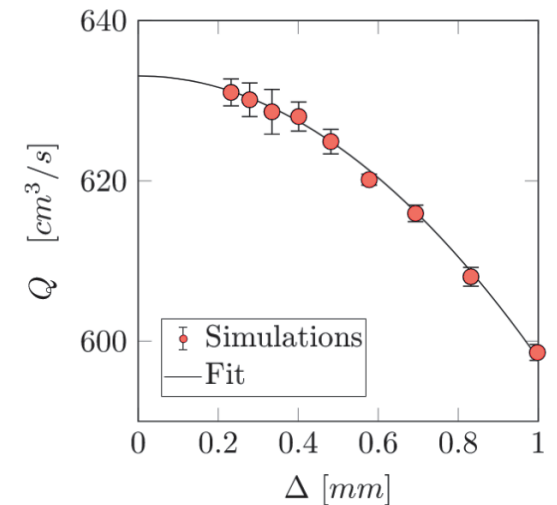
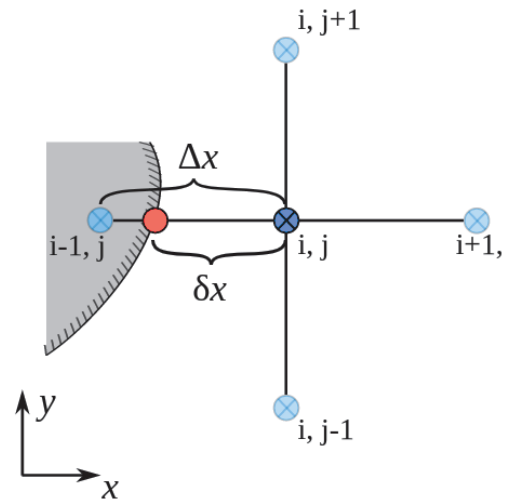


The immersed-boundary method

Hypothesis^a: Laplacian is dominant near the wall

- ▶ 2nd-order accurate
- ▶ stable (correction is implicit)
- ▶ efficient (computing, RAM, workflow)

^aP.Luchini et al, A simple and efficient second-order immersed-boundary method for the incompressible Navier–Stokes equations, J. Comp. Phys 2025

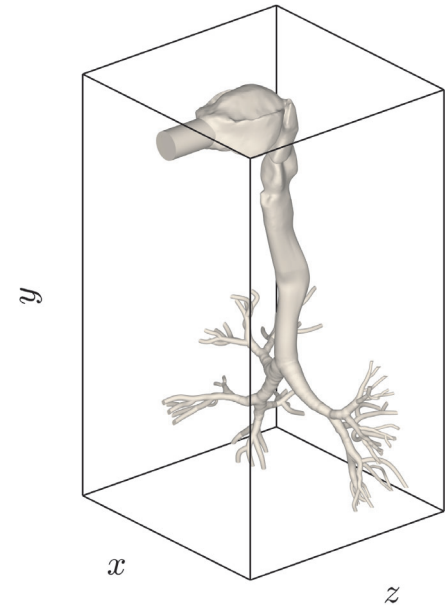


The building-cube method

Separates domain **decomposition** and **parallelization**, addressing:

- ▶ memory waste in solid regions
- ▶ load balancing
- ▶ flexibility

A **Cube** is a portion of the domain, empty cubes are pruned, each parallel thread manages multiple cubes

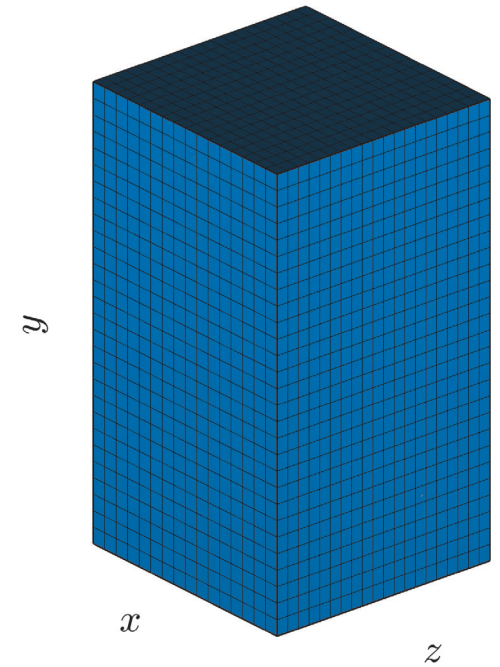


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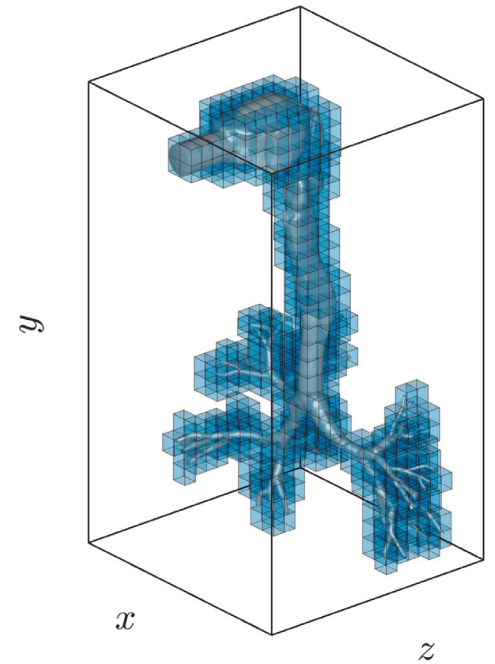


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Performance

- ▶ (multi)GPU programming with OpenACC
- ▶ Fast and resource-efficient
- ▶ Streamlined workflow
- ▶ in double precision: 120B/point; 7×10^{-10} seconds/point/timestep on an (old) A100 GPU

Source, documentation and tutorials on www.amphibious.cfd

An ad-hoc physical model for the nose flow

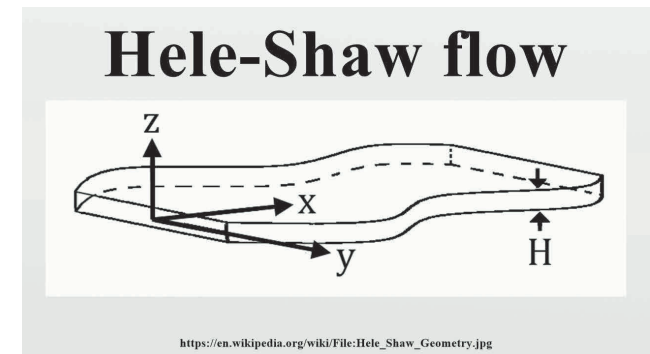
Geometric information is the major limiting factor

- ▶ 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)
- ▶ Need to account for heat transfer (cfr. ENS)



The reduced model

- ▶ 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

Work in progress to understand the model **and** the objective function

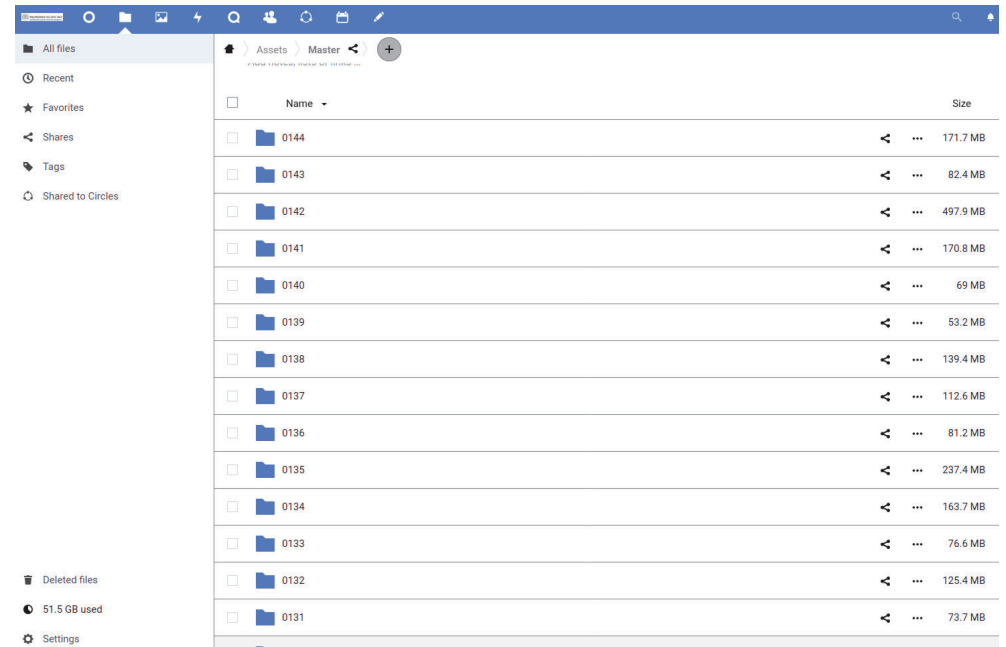
Ad-hoc ML tools

First things first: data!

Database of:

- ▶ CT scans
- ▶ rhinomanometry data
- ▶ ENT evaluation sheet

Open and labeled data: huge value!

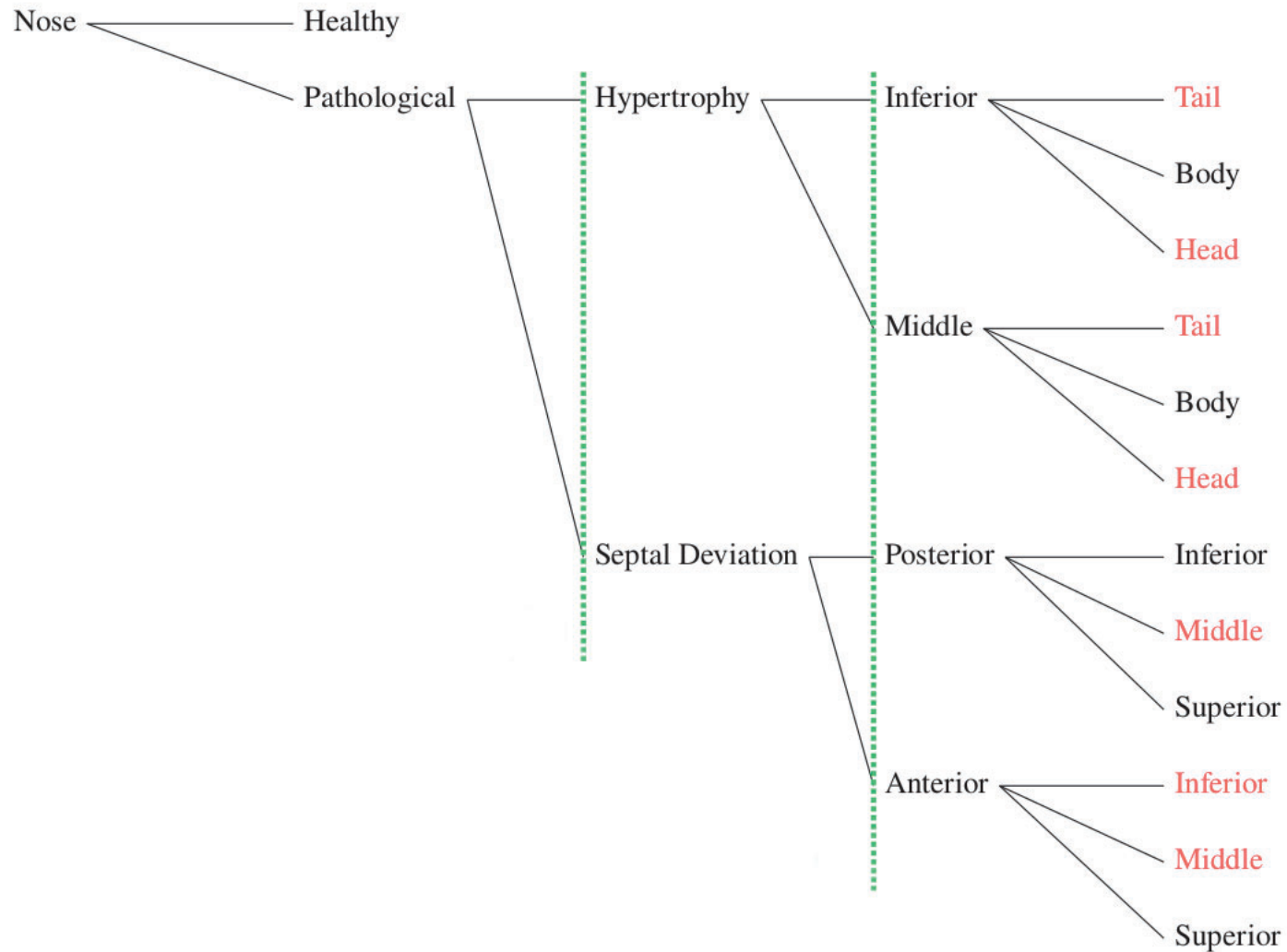


Name	Size
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0142	497.9 MB
0141	170.8 MB
0140	69 MB
0139	53.2 MB
0138	139.4 MB
0137	112.6 MB
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0133	76.6 MB
0132	125.4 MB
0131	73.7 MB

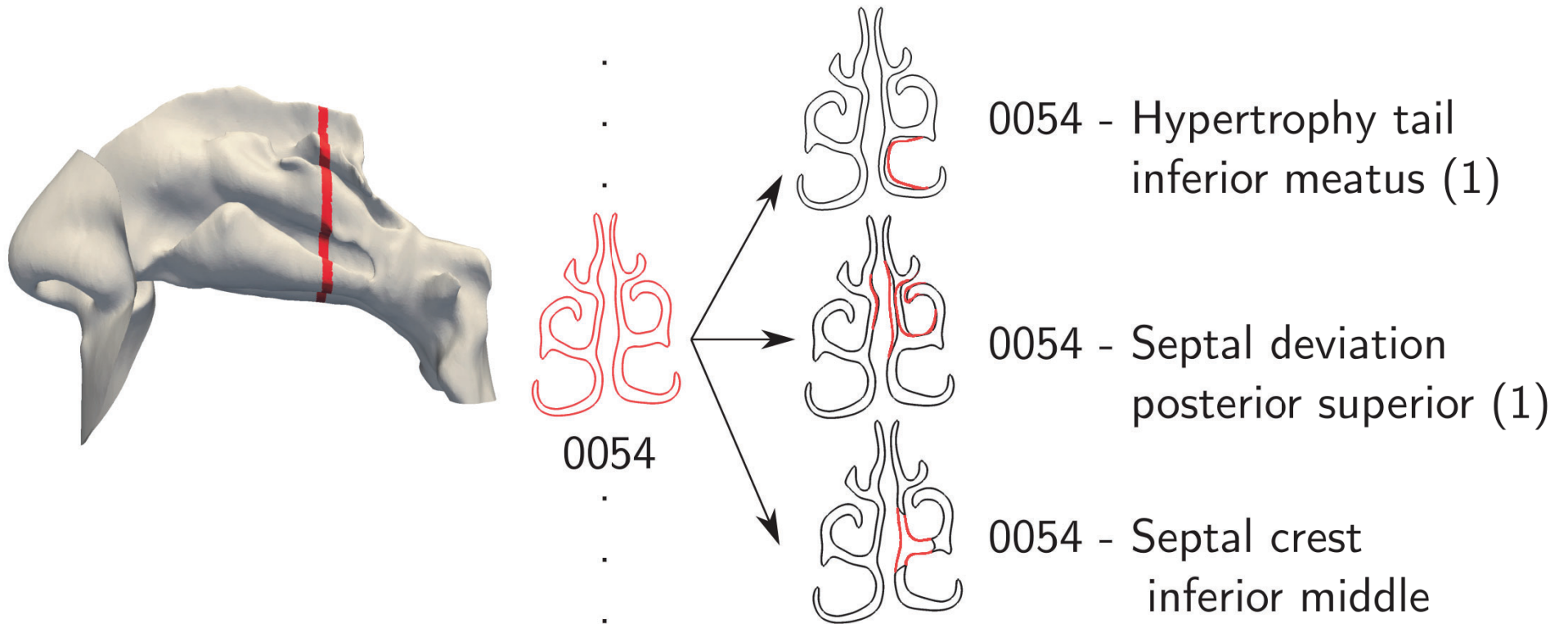
CFD-augmented ML

- ▶ Input to ML is not the CT scan (cost, inaccuracy)
- ▶ Input to ML is the CFD computed on the CT scan
- ▶ **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/surgeries

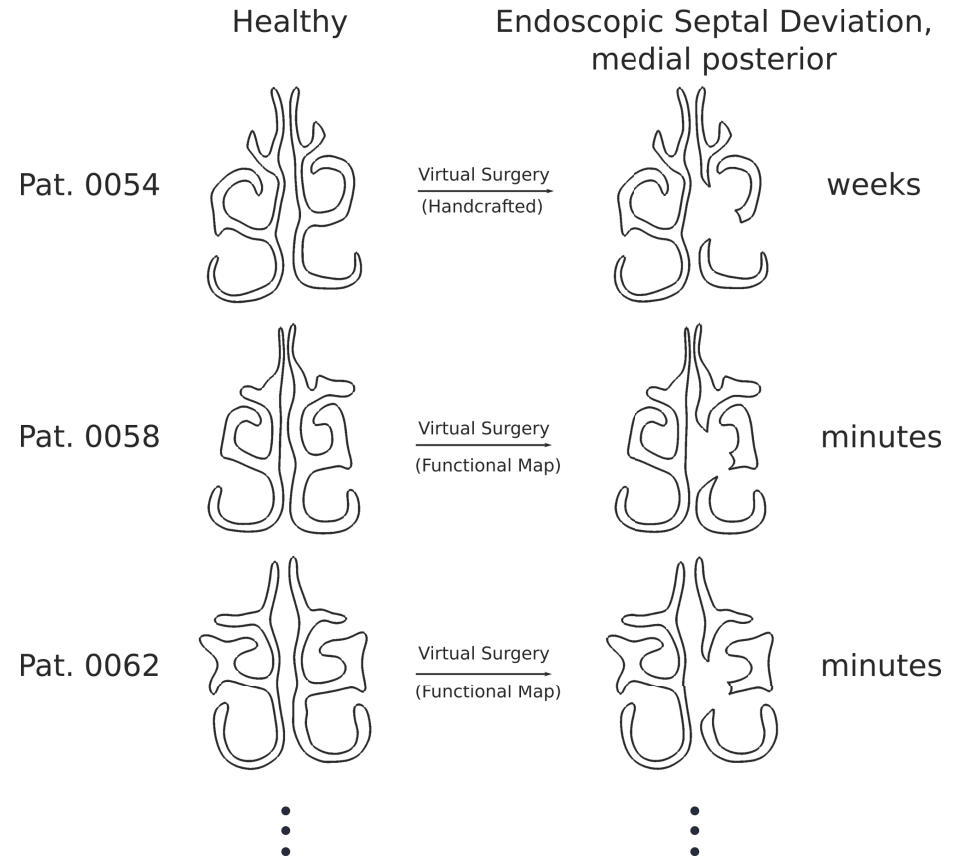


Step 2. Inject elementary defects on one **healthy** patient via **virtual anti-surgeries**



Step 3. Transfer defects automatically 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^a**



^aOvsjanikov *et al.*, ACM Trans. Graphics 2012

Step 4. Create the database with CFD

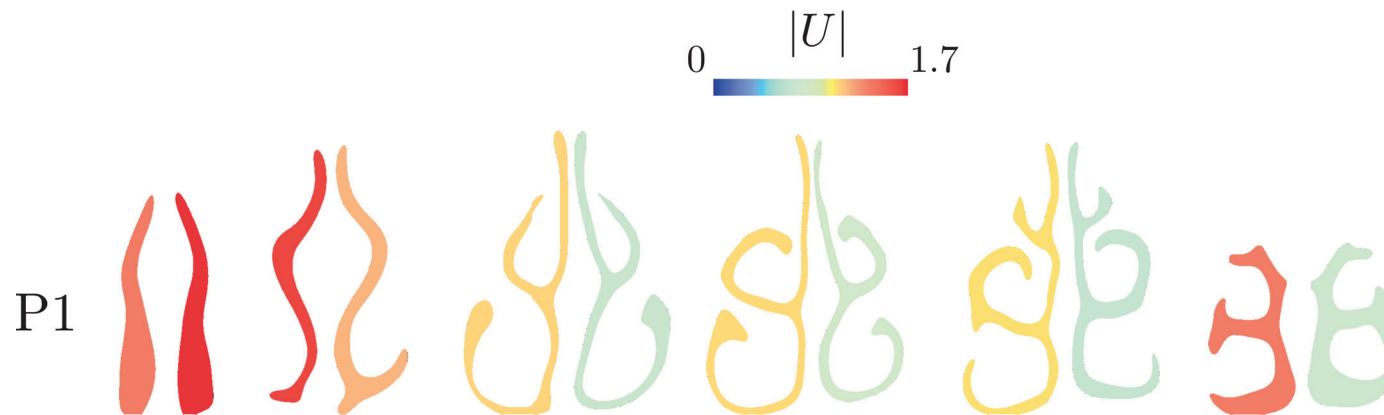
- ▶ 277 distinct anatomies are generated from 7 healthy patients
- ▶ Defects are isolated or in combination, various severities
- ▶ Classes are relatively balanced (but for the healthy class)
- ▶ OpenFOAM (!) is used to compute the flow field (by well resolved LES)

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

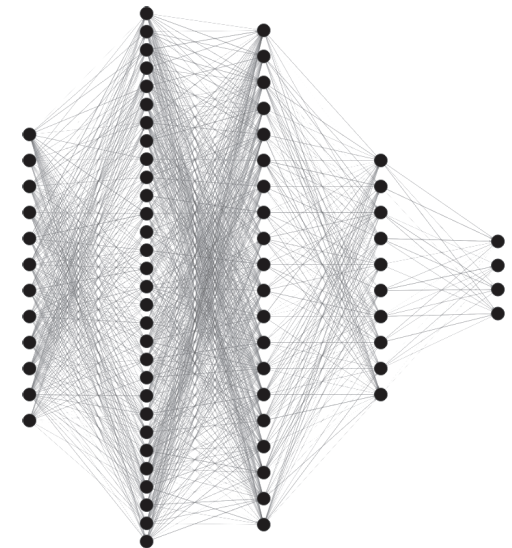
Two strategies: **regional averages** (of velocity, vorticity, TKE, strain, pressure, pressure gradient, etc), and line integral over **streamlines**



A neural network to classify pathologies

- ▶ A standard **neural network** is trained to classify pathologies
- ▶ LOO-CV (preferred to *k*-fold CV) as **partition method** to carry out validation and testing
- ▶ 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

Our classifier (12 inputs, 4 outputs):



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

Concluding remarks

- ▶ The nose flow is a scarcely known but **interesting** topic
- ▶ Multi-disciplinary: CFD, turbulence, flow control, numerical methods, HPC, adjoint optimization, Machine Learning (plus radiology, physiology, otorhinolaryngology, surgery, etc!)
- ▶ Promising to make a difference for problems of **clinical interest**

Acknowledgment to the OpenNOSE group!

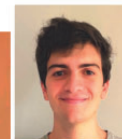
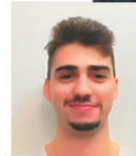
EXPERIMENTS



SURGEONS



**MACHINE
LEARNING**



CFD

The dataset needs to grow further

