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The OpenNOSE project: reasons of interest for the lung modelling community

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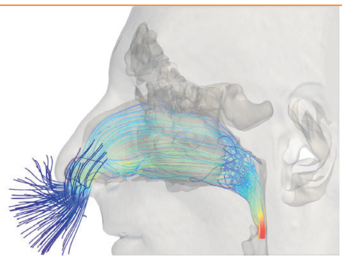
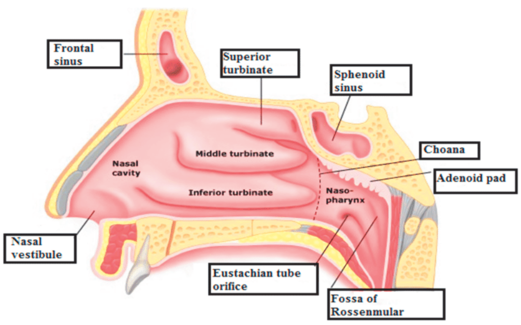
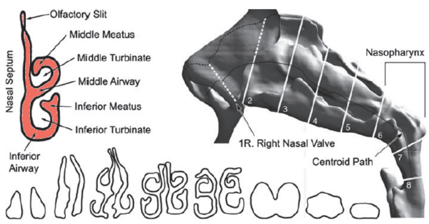
Lung Modelling Congress, Parma, Nov 22–23, 2023



The human nose: functions and anatomy





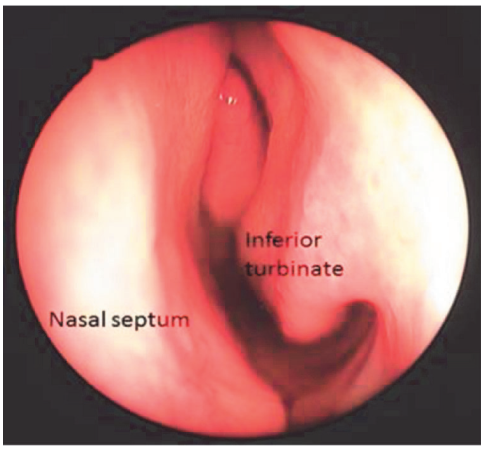
Is the nose flow important?

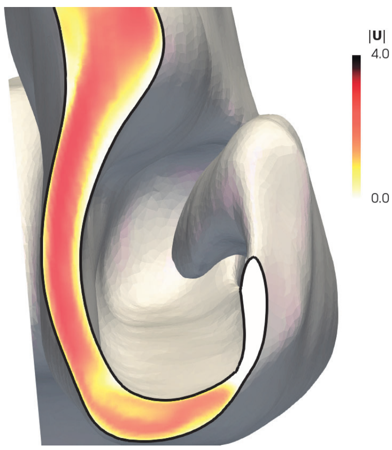
- At least 1/3 of the adult world population is troubled with nasal breathing difficulties[1]
- In 2014, the one-year (only!) cost of cronic rhinosinusits (alone!) in US (only!) was $22bn[2]
- Certain nose surgeries have 50% failure rate[3]

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

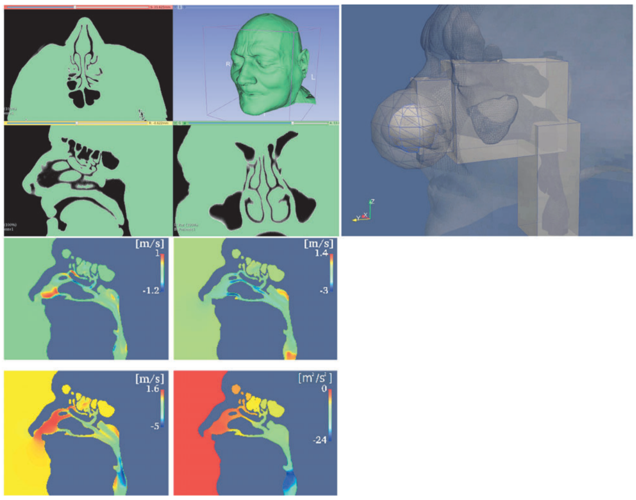
Form *and* function





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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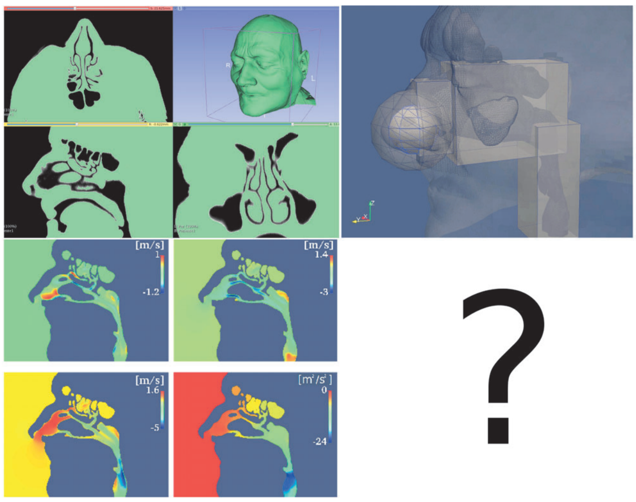

?

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
- Strong inter-subject anatomical variations with different functional significance
- Shape optimization problem, with unknown objective function

OpenNOSE

How to (openly) proceed?

Bringing CFD into the clinical setting requires:

1. Assessing reliability through a solid benchmark
2. Distilling CFD into something useful

Establishing a 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!

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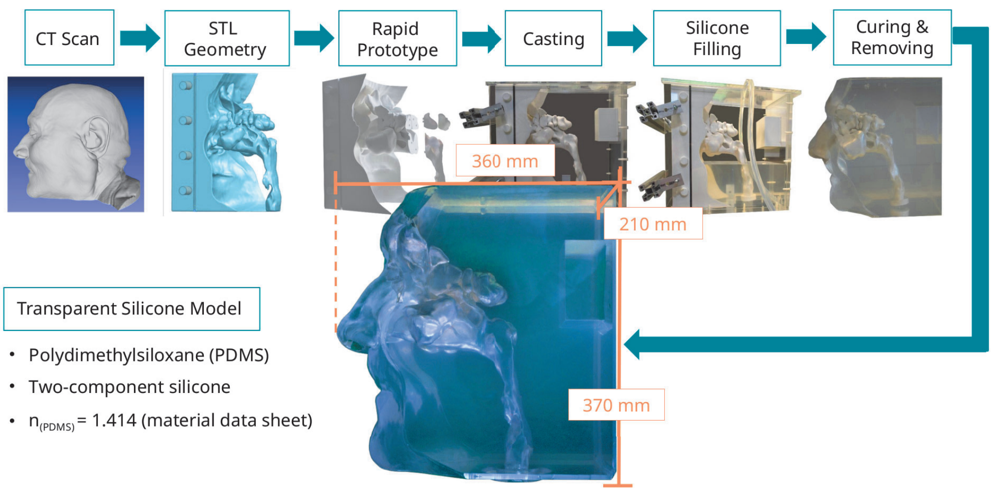
Creating a benchmark: a tomo-PIV experiment

Transparent Silicone Model



Transparent Silicone Model

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

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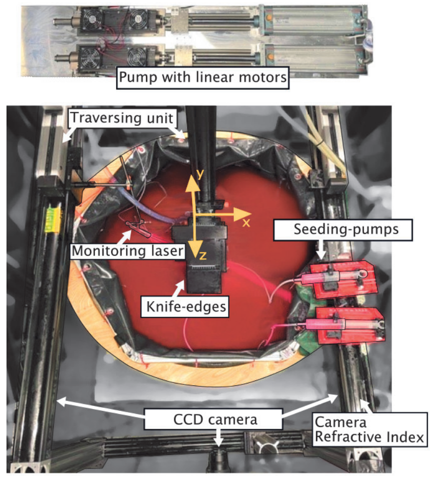
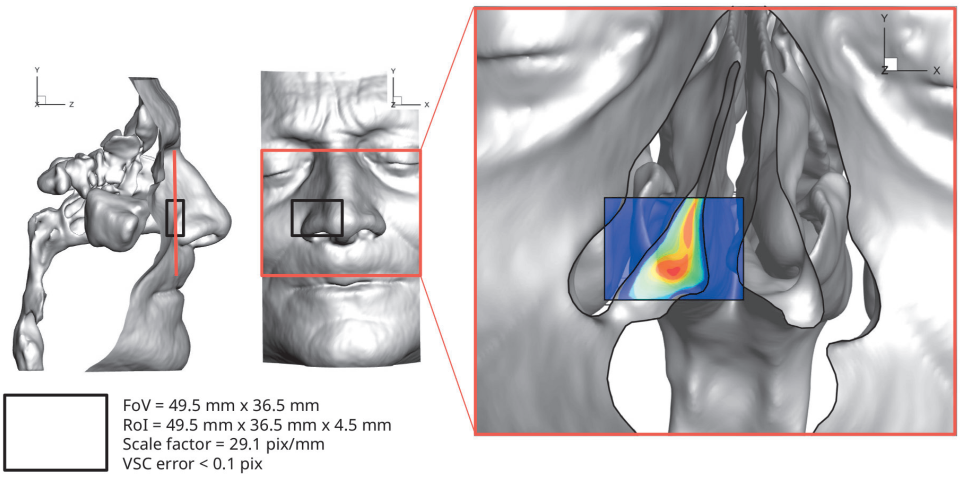
The experimental setup

- 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



The (future) OpenNOSE community

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

Using CFD in clinics (3 attempts)

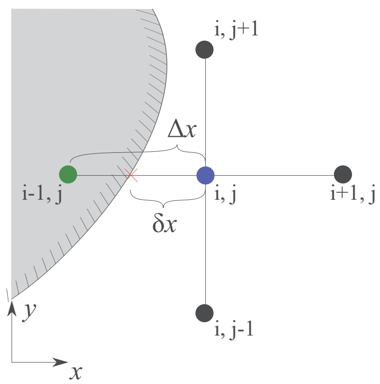
Requirements of a clinically viable CFD

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

- Time
- Skills
- Money

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

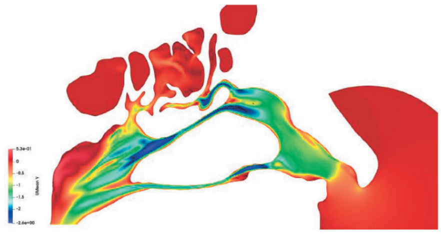
- II-order in space, staggered grid, linear extrapolation
- II-order in time but implicit (stable when grid point approaches boundary)
- Computing and storing solution at ghost nodes is not required
- Simple and efficient: it modifies the central weight of the Laplacian only
- Extrapolations in the 3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



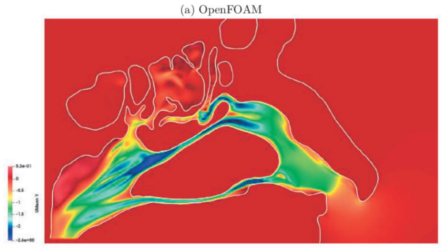
CPL: Compiler and Programming Language, `https://cplcode.net`

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?)



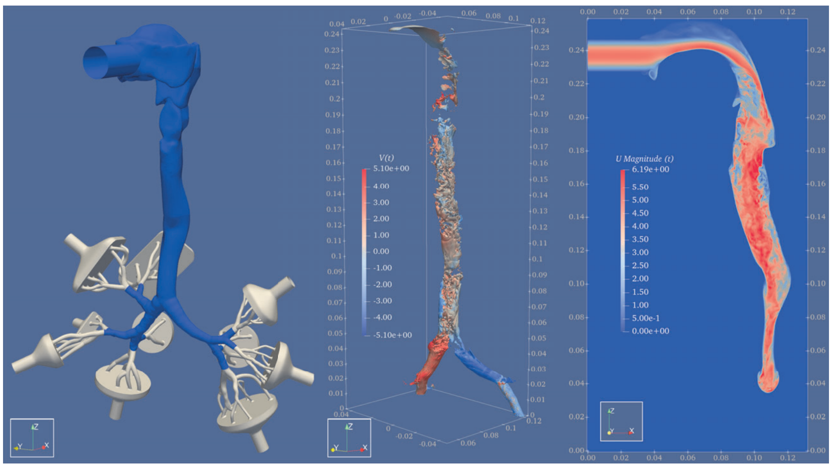
(a) OpenFOAM



(b) STLIMB

Towards DNS of the lung flow: the SimInhale model

Ongoing work with Chiesi



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)

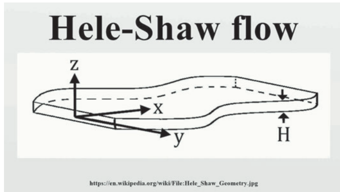
Nasal resistance is not telling the whole story

- 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

- Less than Navier–Stokes suffices to compute nasal resistance
- A quasi-1d approximation in the ”narrow” direction: Hele–Shaw extended to a non-planar channel (with temperature)
- Local porosity computed for each voxel as a function of the wall distance
- Reconstruction, segmentation, meshing are all 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

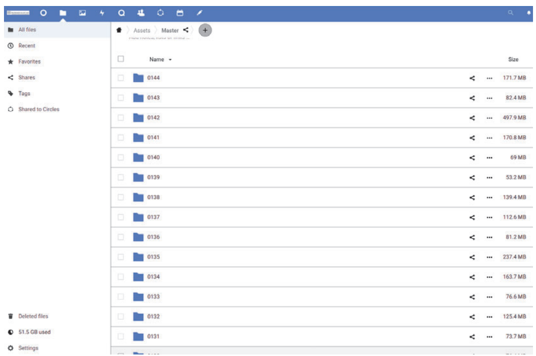
- Issue: anatomic variability is too large, we won't have enough labelled data
- Proposed solution: augment ML with CFD
- Hypothesis: the flow field amplifies anatomic information

Pb.1: Obtaining data to train the NN

Database of:

- CT scans
- rhinomanometry data
- ENT evaluation sheet

Open and labeled data: huge value!

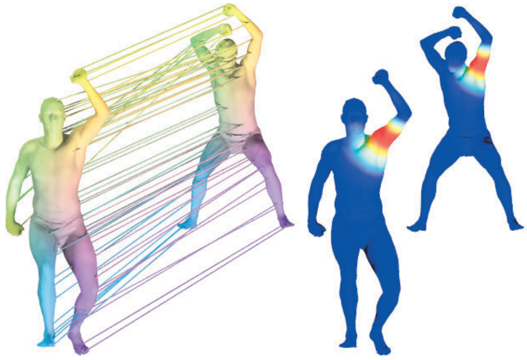


Pb.2: Reducing dimensionality of the CFD

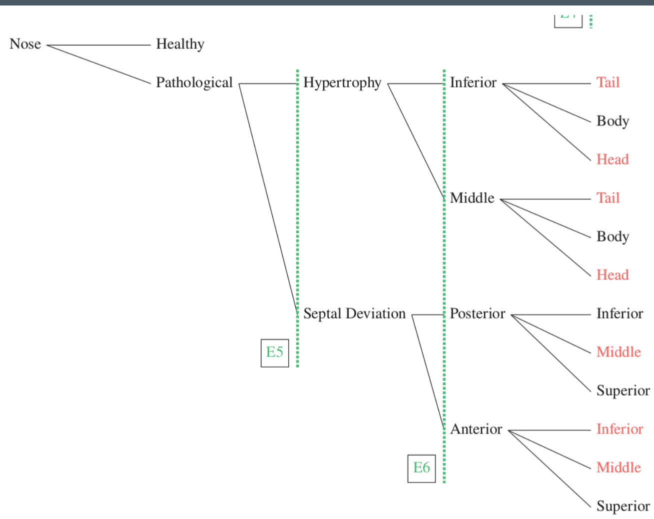
Features are computed with functional mapping[a] (FM)

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

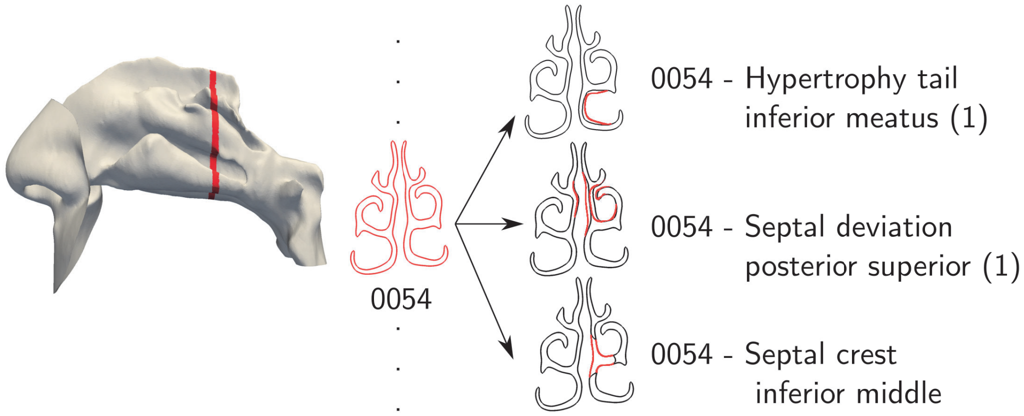
[a] M.Ovsjanikov *et al.* ACM Trans. Graph. 2012



Step 1. Define a tree of elementary defects

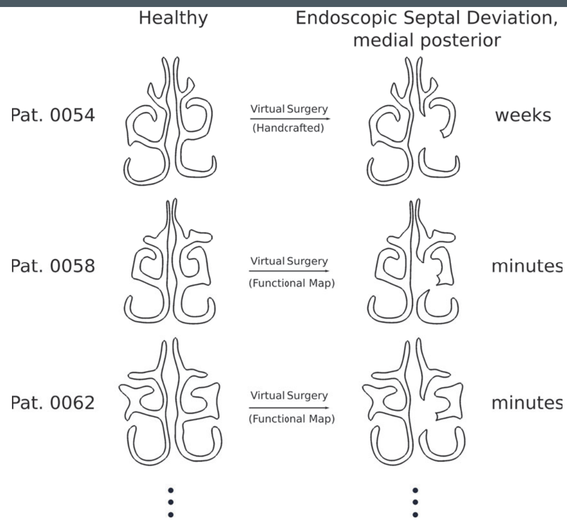


Step 2. Create atomic defects via virtual anti-surgeries



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

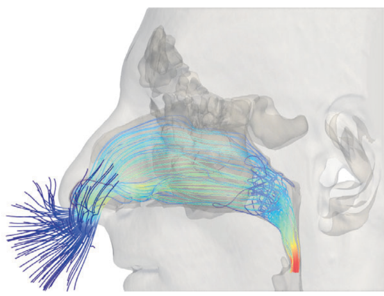


Step 4. Run CFD to create the database

- 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)
- CFD (LES/DNS) is used to compute the flow field

The OpenFOAM setup

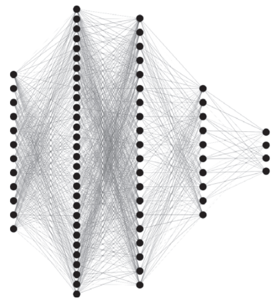
- Steady inspiration at 280 ml/s (mild breathing)
- Well resolved (incompressible) LES
- Mesh with 15M cells, no layers, $\nu_t/\nu < 4.4$
- All terms at second-order accuracy
- Statistics computed over 0.6 s
- 7000 core hours for each case



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):

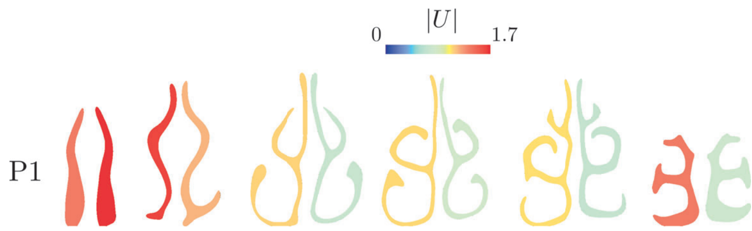


Converting CFD to a small feature set

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
- Lots of ongoing work...

Concluding remarks

- The nose flow is an interesting, high-potential interdisciplinary topic
- CFD-augmented ML techniques are promising
- CFD has a bright future in medicine
- OPEN is a key word

Acknowledgment to the OpenNOSE group!