



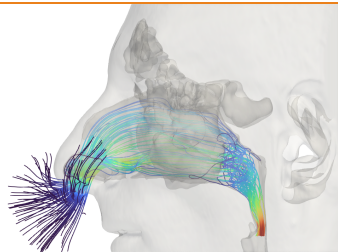
POLITECNICO
MILANO 1863

DIPARTIMENTO DI SCIENZE
E TECNOLOGIE AEROSPAZIALI

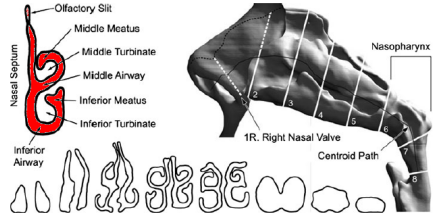
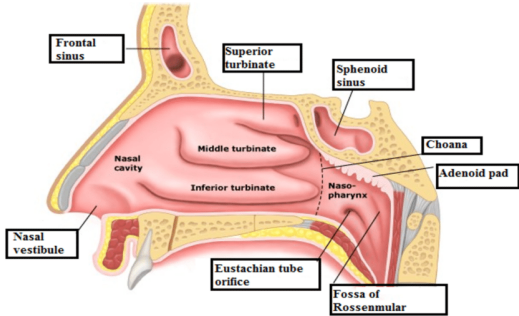
Fluid Dynamics of the Human Nose: An overview of clinical perspectives enabled by CFD

Maurizio Quadrio

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 difficulties¹
- ▶ In 2014, the one-year (only!) cost of cronic rhinosinusits (alone!) in US (only!) was \$22bn²
- ▶ Certain nose surgeries have 50% failure rate³

Huge **room for improvement!**

¹Stewart *et al.* Int J Gen Med 2010

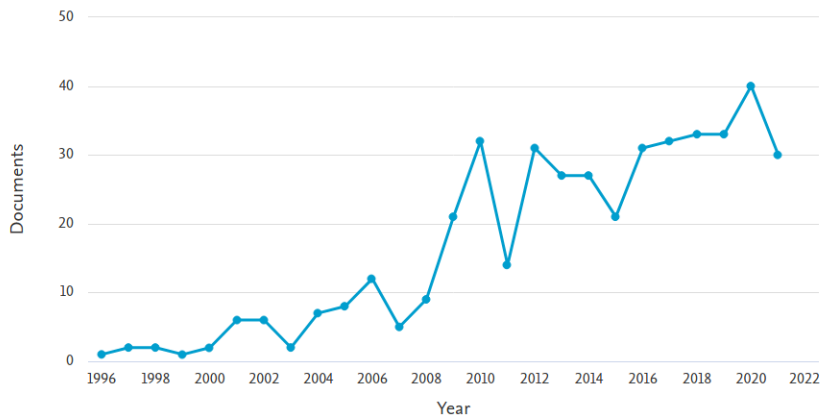
²Smith *et al.* The Laryngoscope 2015

³Sundh & Sonnergreen, Eur Arch Otholaringol 2015

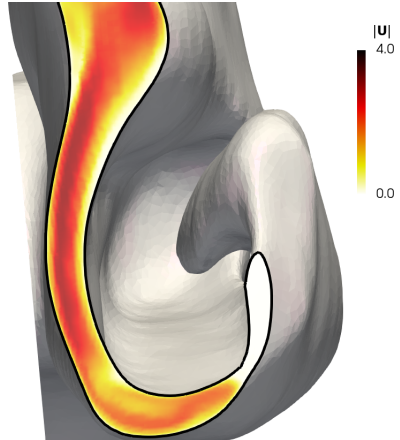
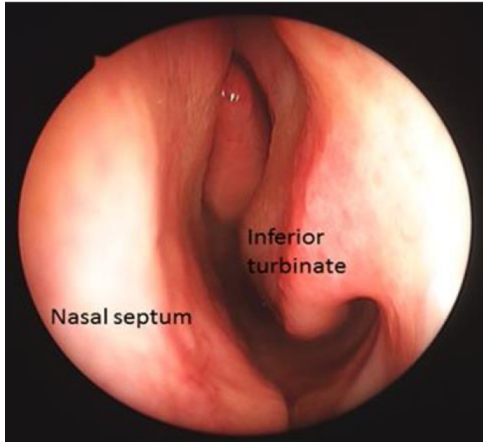
The contribution of fluid mechanics

Scopus query: "CFD" + "nasal"

Documents by year

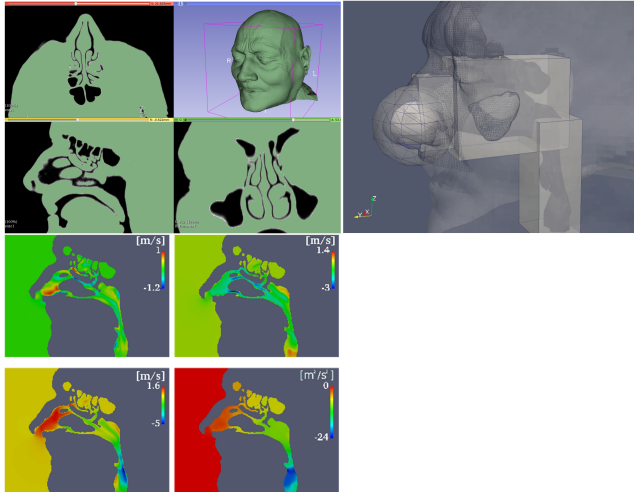


Form and function



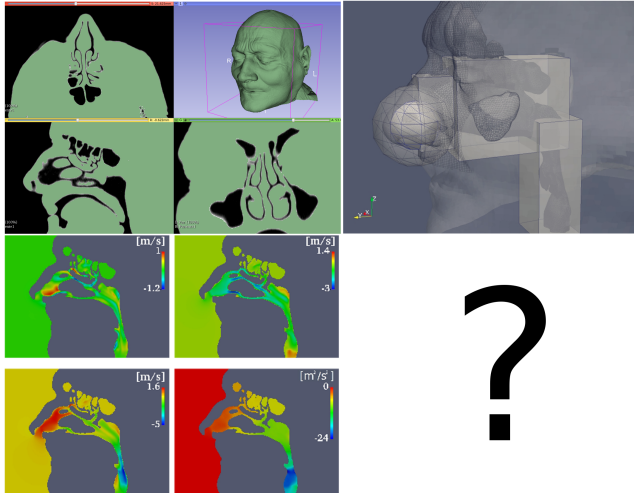
The workflow: from CT scan to...

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



The workflow: from CT scan to...

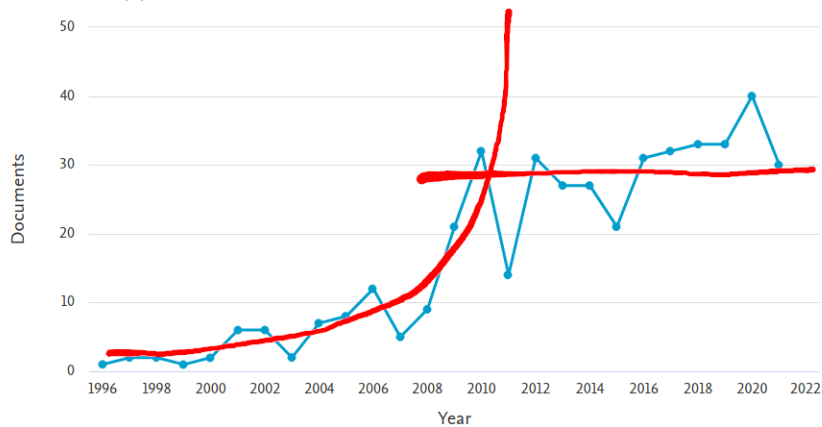
1. Segment the CT scan
2. Build a volume mesh
3. Compute a CFD solution (DNS, LES, RANS, ...)



Only academic?

Scopus query: "CFD" + "nasal"

Documents by year



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

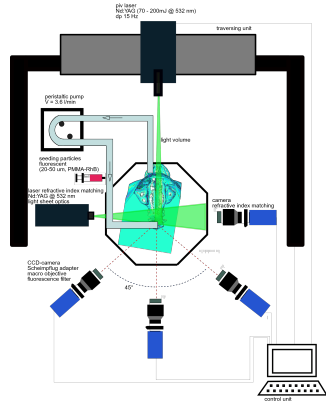
The benchmark

- ▶ 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

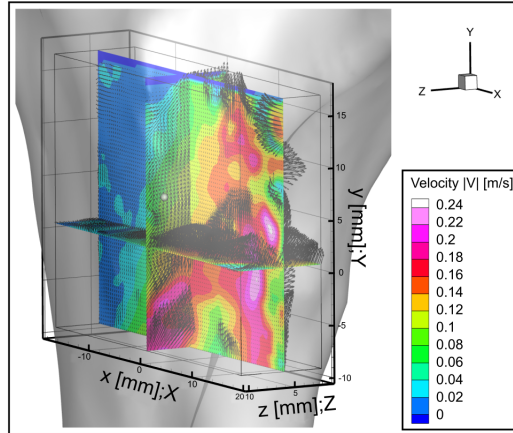
The major limiting factor is **lack of reproducibility**: anatomies are sensible information!

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



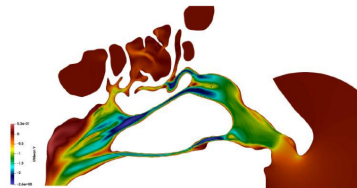
Is CFD clinically viable?

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

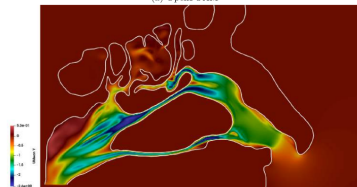
- ▶ Money
- ▶ Time
- ▶ Skills

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

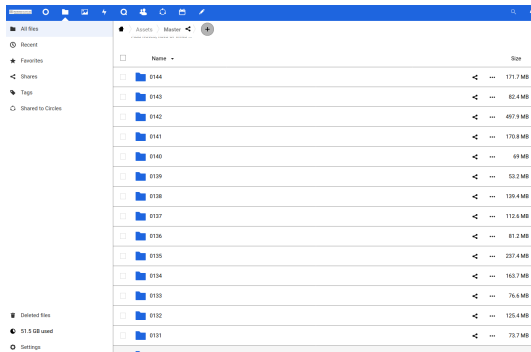
- ▶ Main reason: lack of functionally normal reference nose
- ▶ Shape optimization problem, but an **objective function is lacking**
- ▶ Strong inter-subject anatomical variations with different functional significance

We pursue two approaches, **without** and **with** an objective function

Database of:

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

Open and labeled data: huge value!



The screenshot shows a file explorer window with a list of folders. The folders are named with four-digit numbers (e.g., 0144, 0143, 0142, 0141, 0140, 0139, 0138, 0137, 0136, 0135, 0134, 0133, 0132, 0131). The sizes of these folders range from 76.6 MB to 497.9 MB. The interface includes a left sidebar with navigation options like 'All files', 'Recent', 'Favorites', 'Shares', 'Tags', and 'Shared to Circles'. At the bottom, it shows 'Deleted files', '51.5 GB used', and 'Settings'.

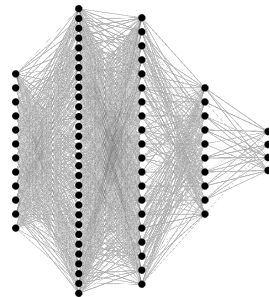
Name	Size
0144	171.7 MB
0143	82.4 MB
0142	497.9 MB
0141	170.8 MB
0140	69 MB
0139	53.2 MB
0138	130.4 MB
0137	112.6 MB
0136	81.2 MB
0135	237.4 MB
0134	168.7 MB
0133	76.6 MB
0132	126.4 MB
0131	73.7 MB

- ▶ 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

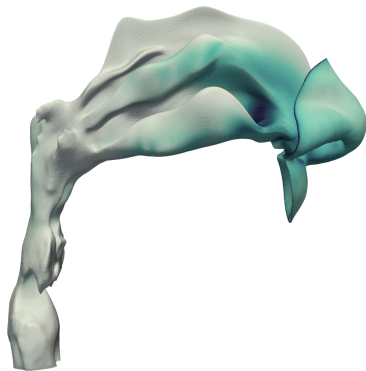
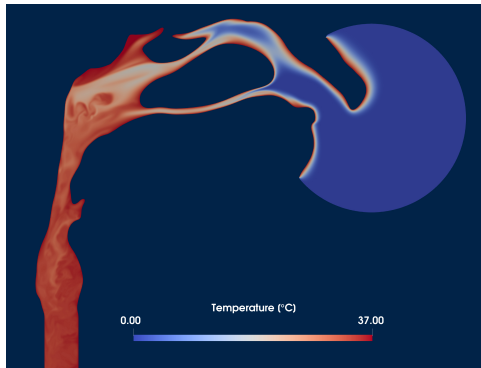
- ▶ A tree of deformations is built based on an orthogonal basis of **primitive surgeries**
- ▶ A number of healthy patients is given a combination of pathologies
- ▶ For ≈ 300 combinations, a hi-fi CFD solution is computed
- ▶ A **neural network** is trained to classify classes of pathologies
- ▶ Details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

Our classifier:



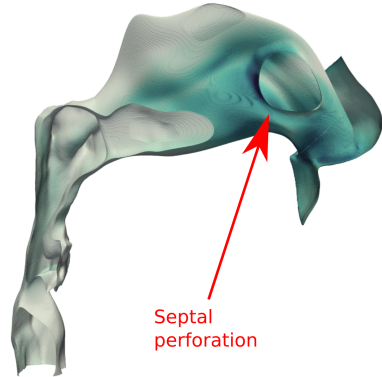
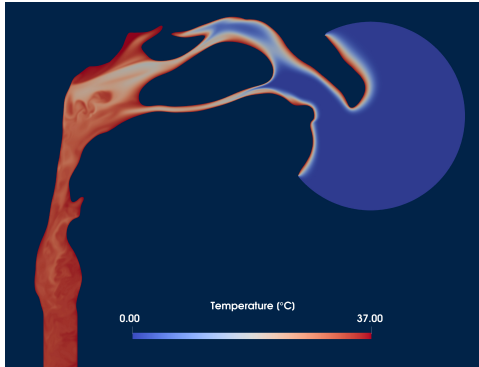
Bringing physics into the picture

Example: warming of **cold air** during inhalation



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

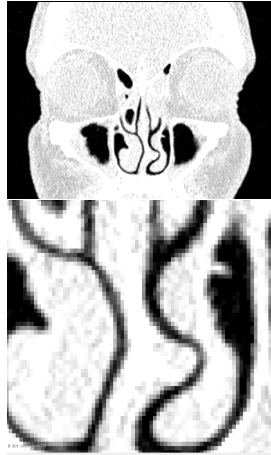
Critical for **septal perforations**



Exploiting physics to find an objective function

Geometric information is the major limiting factor

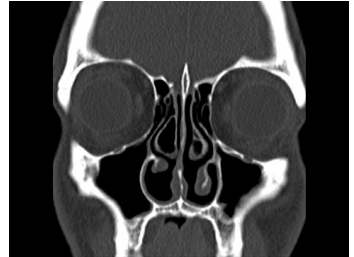
- ▶ Thickness of the **nasal fossae** is often 1-2 voxels (even less for pathologies)
- ▶ No less than the **CT grid** must be used (typically 512^3)
- ▶ Explicit reconstruction, segmentation, meshing are avoided



Nasal resistance is not telling the whole story

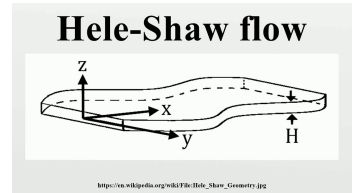
- ▶ Restoring a good Nasal Resistance is not enough
- ▶ Cfr. the "Empty Nose Syndrome"
- ▶ **Heat transfer** characteristics must be also considered!

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

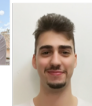
- ▶ Active research thread with great potential
- ▶ **Clinically** relevant
- ▶ Highly **multi-disciplinary**: CFD, turbulence, modeling, flow control, numerics, shape optimization, Machine Learning, etc

Acknowledgment to the OpenNOSE gang!

EXPERIMENTS



**MACHINE
LEARNING**



SURGEONS



CFD

